


"十三五"普通高等教育本科规划教材
高等院校汽车专业"互联网+"创新规划教材

（双语教学版）

# 汽车新能源与排放控制

# New Energy and Emission Control for Automobiles

周庆辉　编著





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## 内 容 提 要

本书根据近年来多种英语公开资料编写形成，共分 8 章，从汽车排放控制的角度出发，首先分析排放污染物的生成机理，由浅入深、循序渐进地介绍汽车新能源技术，探讨汽车排放控制的问题，此外还扼要阐述国内外汽车排放标准的发展。第 1 章介绍汽车排放与环境的关系；第 2 章分析汽车排放污染物及其生成机理；第 3 章、第 4 章和第 5 章分别介绍了电动汽车、混合动力汽车和低排放燃料汽车；第 6 章和第 7 章分别详细分析了汽油机和柴油机排放控制技术；第 8 章简明扼要地分析了国内外汽车排放管理状况，包括排放标准的发展过程。

本书可作为高等院校车辆工程、能源与动力工程、汽车服务工程、环境工程等专业应用型本科学生的双语教学教材，也可以作为其他相关专业工程技术人员和管理人员的培训教材。

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# 前　　言

随着汽车保有量持续增长，石油燃料大量消耗，排放污染物总量持续攀升，尤其在一些大中城市汽车排放造成的环境污染问题日趋严重。发展新能源汽车，推动产业升级，有利于保护和改善环境。为了加强汽车新能源与排放控制技术的国际化交流，需要学习大量的英文技术资料。本书综合了国内外最新相关资料和相关研究成果，系统地介绍和讨论了汽车新能源与排放控制相关的新知识、新技术和新内容，并且配合双语教学，使学生掌握一定数量的专业词汇，提高英语的应用能力。

本书共分 8 章：第 1 章介绍汽车排放与环境的关系；第 2 章分析汽车排放污染物及其生成机理；第 3 章、第 4 章和第 5 章分别介绍了电动汽车、混合动力汽车和低排放燃料汽车；第 6 章和第 7 章分别详细分析了汽油机和柴油机排放控制技术；第 8 章简明扼要地分析了国内外汽车排放管理状况，包括标准的发展过程。

本书的特色和价值：

（1）内容先进。新能源汽车不断发展，汽车排放标准不断严格。新标准也带来了技术上的革新。本书从内容上结合国内外最新相关资料，介绍新能源和排放控制技术。

（2）选材新颖。选材参考了欧盟、美国、日本等国家和地区的最新排放法规和排放标准，世界著名汽车公司的相关技术资料和研究成果。

（3）语言通俗。语言简练，通俗易懂，适合于本科学生和相关专业工程技术人员。

（4）结构合理。

（5）教学适用。

本书由北京建筑大学周庆辉统筹并编写。在编写的过程中，得到了中国农业大学纪威教授，北京建筑大学杨建伟教授、孙建民教授、朱爱华副教授及陈展、陆斯媛硕士研究生等的帮助，并得到了北京大学出版社的大力支持，在此表示感谢。

由于编者水平有限，疏漏在所难免，敬请广大读者给予批评指正。

编　者

2016 年 4 月





【精彩汇总】

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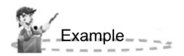
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# Chapter 1

## Introduction






You see it every time that smoke billows from your car's exhaust pipe in the Figure 1.1, so there's no denying that vehicles are major contributors to air pollution. Air pollution refers to the presence of other substances in the air that don't belong there, or excessive amounts of certain impurities that wouldn't harm us otherwise. When cars burn gasoline, certain chemicals are released into the air. Gasoline fumes escape into the air even when we pump gasoline into the fuel tanks.

Air pollution is the introduction of particulates, biological molecules, or other harmful materials into Earth's atmosphere, causing diseases, allergies, death to humans, damage to other living organisms such as animals and food crops, or the natural or built environment.





【参考视频】

**Figure 1.1  Exhaust from Tailpipe**

Question: How many major pollutants come from cars?

# 1.1 Air Pollution and Vehicles

### 1.1.1 Air Pollution

Air pollution is the introduction of particulates, biological molecules, or other harmful materials into Earth's atmosphere, causing diseases, death to humans, and damage to other living organisms such as animals and food crops, or the natural or built environment. Air pollution may come from anthropogenic or natural sources.

The atmosphere is a complex natural gaseous system that is essential to support life on planet Earth, as shown in Figure 1.2. Stratospheric ozone depletion due to air pollution has been recognized as a threat to human health as well as to the Earth's ecosystems.



【参考视频】

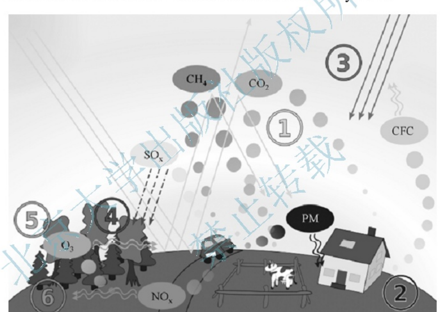



**Figure 1.2 Schematic drawing, causes and effects of air pollution: (1) greenhouse effect, (2) particulate contamination, (3) increased UV radiation, (4) acid rain, (5) increased ground level ozone concentration, (6) increased levels of nitrogen oxides.**

### 1.1.2 Sources

There are various sources that are responsible for releasing pollutants into the atmosphere, which can be classified into two major categories.

#### 1.1.2.1 Anthropogenic sources

These sources are mostly related to the burning of multiple types of fuel.

✧ Stationary sources include smoke stacks of power plants, manufacturing facilities (factories) and waste incinerators, as well as furnaces and other types of fuel-burning

heating devices. In some developing and poor countries, traditional biomass burning is the major source of air pollutants; traditional biomass includes wood, crop waste and dung.

✧ Mobile sources include motor vehicles, marine vessels, and aircraft.

#### 1.1.2.2 Natural sources

✧ Dust from natural sources, usually large areas of land with little or no vegetation

✧ Smoke and carbon monoxide from wildfires

Emissions from cars increase the levels of carbon dioxide and other greenhouse gases in the atmosphere. At normal levels, greenhouse gases keep some of the sun's heat in the atmosphere and help warm Earth. That said, many scientists believe that burning fossil fuels such as gasoline causes greenhouse gas levels to spike, leading to global warming.

Scientists use sophisticated instruments to measure concentrations of harmful substances in the air, but it's tough to say exactly what percentage of air pollution comes from cars. This makes sense, because many other human activities contribute to air pollution as well. In fact, the production of electricity by coal-fired power plants and other sources can cause more pollution than most cars. If that wasn't enough, we pollute the air when we heat our homes and public buildings with fuels other than electricity — just as we do when we drive our cars. Even people who don't drive add to pollution when they buy goods and services that involve fuel when they're made or delivered.

In 2013, transportation contributed more than half of the carbon monoxide and nitrogen oxides, and almost a quarter of the hydrocarbons emitted into our air. Cars and trucks produce air pollution throughout their life, including pollution emitted during vehicle operation, refueling, manufacturing, and disposal. Additional emissions are associated with the refining and distribution of vehicle fuel.

Pollutants from cars contribute to various types of air pollution. When hydrocarbons and $NO_x$ combine in sunlight, they produce ozone. High in the atmosphere, ozone protects us from the sun's ultraviolet rays. When holes in the atmosphere's ozone layer allow ozone to come closer to Earth, it contributes to smog and causes respiratory problems.

Air pollutants emitted from cars are believed to cause cancer and contribute to such problems as asthma, heart disease, birth defects and eye irritation.

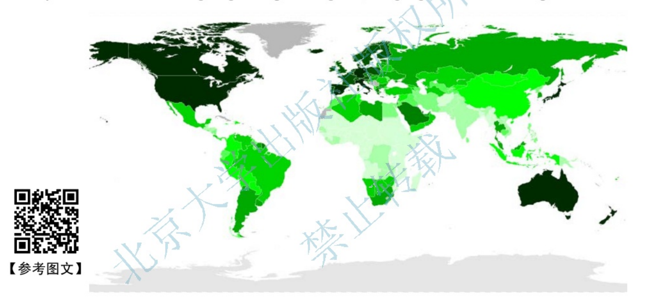
## 1.2 Environmental Impact

While there are different types of fuel that may power cars, most rely on gasoline or diesel. The United States Environmental Protection Agency(EPA)states that the average vehicle emits 8,887 grams of carbon dioxide per gallon of gasoline. The average vehicle running on diesel fuel

will emit 10,180 grams of carbon dioxide. Many governments are using fiscal policies (such as road tax or the US gas guzzler tax) to influence vehicle purchase decisions, with a low $CO_2$ figure often resulting in reduced taxation. Fuel taxes may act as an incentive for the production of more efficient, hence less polluting, car designs (e.g. hybrid vehicles) and the development of alternative fuels. High fuel taxes may provide a strong incentive for consumers to purchase lighter, smaller, more fuel-efficient cars, or to not drive. On average, today's automobiles are about 75 percent recyclable, and using recycled steel helps reduce energy use and pollution.

The manufacture of vehicles is resource intensive, and many manufacturers now report on the environmental performance of their factories, including energy usage, waste and water consumption.

The growth in popularity of the car allowed cities to sprawl, therefore encouraging more travel by car resulting in inactivity and obesity, which in turn can lead to increased risk of a variety of diseases.World map of passenger cars per 1,000 people as shown in Figure 1.3.



【参考图文】



**Figure 1.3 Worold map of passenger cars per 1,000 people**

Transportation (of all types including trucks, buses and cars) is a major contributor to air pollution in most industrialised nations. According to the American Surface Transportation Policy Project nearly half of all Americans are breathing unhealthy air. Their study showed air quality in dozens of metropolitan areas has worsened over the last decade.

Similarly, China's environmental protection ministry published a report in November 2010 which showed that about a third of 113 cities surveyed failed to meet national air standards last year. According to the World Bank, 16 of the world's 20 cities with the worst air are in China. According to Chinese government sources, about a fifth of urban Chinese breath heavily polluted air. Many places smell like high-sulfur coal and leaded gasoline. Only a third of the 340 Chinese cities that are monitored meet China's own pollution standards. It is the pollution in Beijing in 2013, as shown in the Figure 1.4.






**Figure 1.4 Pollution in Beijing in 2013**



Animals and plants are often negatively impacted by cars via habitat destruction and pollution. Over the lifetime of the average car the "loss of habitat potential" may be over 50,000 square meters based on primary production correlations. Animals are also killed every year on roads by cars, referred to as roadkill. More recent road developments are including significant environmental mitigation in their designs such as green bridges to allow wildlife crossings, and creating wildlife corridors.

Growth in the popularity of vehicles and commuting has led to traffic congestion. Brussels was considered Europe's most congested city in 2011.

## 1.3 Types of Emissions

Air pollution caused by cars and trucks is split into primary and secondary pollution. Primary pollution is emitted directly into the atmosphere; secondary pollution results from chemical reactions between pollutants in the atmosphere. The following are the major pollutants released from motor vehicles:

### 1.3.1 Nitrogen Oxides ($NO_x$)

Nitrogen oxides ($NO_x$) refers to Nitric oxide(NO) and Nitrogen dioxide($NO_2$). They are produced during combustion, especially at high temperature. These two chemicals are important trace species in Earth's atmosphere. Nitrogen oxides ($NO_x$) react with ammonia, moisture, and other compounds to form nitric acid vapor and related particles. Small particles can penetrate deeply into sensitive lung tissue and damage it, causing premature death in extreme cases. Inhalation of such particles may cause or worsen respiratory diseases such as emphysema and bronchitis. It may also aggravate existing heart disease. In a 2005 U.S. EPA study the largest emissions of $NO_x$ came from on road motor vehicles, with the second largest contributor being

non-road equipment which is mostly gasoline and diesel stations. The resulting nitric acid may be washed into soil, where it becomes nitrate, which is useful to growing plants. Smog in New York City as viewed from the World Trade Center in 1988 is shown in Figure 1.5.


【参考图文】

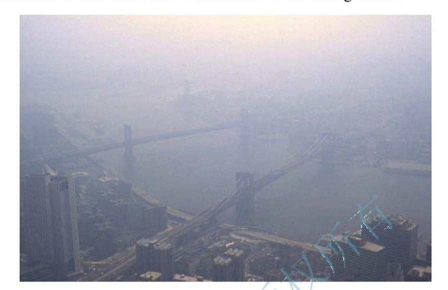


**Figure 1.5  Smog in New York City as viewed from the World Trade Center in 1988**

Using new, high-resolution global satellite maps of air quality indicators, NASA scientists tracked air pollution trends over the last decade in various regions and 195 cities around the globe. The United States, Europe and Japan have improved air quality thanks to emission control regulations, while China, India and the Middle East, with their fast-growing economies and expanding industry, have seen more air pollution in Figure 1.6.




【参考视频】



**Figure 1.6  Nitrogen dioxide 2014—global air quality levels (released 14 December 2015)**

### 1.3.2  Hydrocarbons (HC)

Hydrocarbons are a class of burned or partially burned fuel. These pollutants are a major contributor to smog, which can be a major problem in urban areas. Hydrocarbons can react with

nitrogen oxides in the presence of sunlight to form ground level ozone, a primary ingredient in smog. Though beneficial in the upper atmosphere, at the ground level the gas irritates the respiratory system, causing coughing, choking, and reduced lung capacity.

### 1.3.3 Carbon Monoxide (CO)

Carbon monoxide poisoning is the most common type of fatal air poisoning in many countries. Carbon monoxide is colorless, odorless and tasteless, but highly toxic. It combines with hemoglobin to produce carboxyhemoglobin, which is ineffective for delivering oxygen to bodily tissues. In 2011, 52% of carbon monoxide emissions were created by mobile vehicles in the U.S. Satellite computer image of carbon monoxide March 2010 is shown in Figure 1.7.

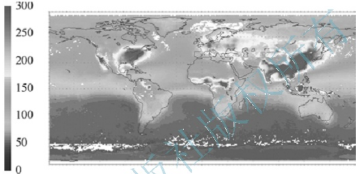






**Figure 1.7 Satellite computer image of carbon monoxide March 2010**



Carbon monoxide inhibits the ability of the blood to carry oxygen, and in particular dangerous to smokers and people with heart disease. It can also cause permanent damage to the nervous system.

### 1.3.4 Particulate Matter (PM)

The health effects of inhaling airborne particulate matter have been widely studied in humans and animals, which include asthma, lung cancer, cardiovascular issues, and premature death. Because of the size of the particles, they can penetrate the deepest part of the lungs. A 2011 UK study estimates 90 deaths per year due to passenger vehicle PM. In a 2006 publication, the U.S. Federal Highway Administration (FHWA) states that in 2002 about 1 percent of all PM10 and 2 percent of all PM2.5(as shown in Figure 1.8) emissions came from the exhaust of on-road motor vehicles (mostly from diesel engines).

Particulate matter (PM) causes lung problems including shortage of breath, cardiovascular disease, damaging lung tissue and cancer. Ultra-fine PM makes its way past the upper airway and penetrates the deepest tissue of the lungs and thence to the blood stream. At concentrations above 5 micrograms per cubic metre particulate matter presents a significant cancer risk. Many PMs are recognized as toxicants and carcinogens, as well as hazards to the reproductive and endocrine systems.

【参考视频】




**Figure 1.8　PM2.5**

### 1.3.5　Volatile Organic Compounds

Volatile organic compounds (VOCs) are organic chemicals that have a high vapor pressure at ordinary room temperature. Their high vapor pressure results from a low boiling point, which causes large numbers of molecules to evaporate or sublimate from the liquid or solid form of the compound and enter the surrounding air, a trait known as volatility. For example, formaldehyde, which evaporates from paint, has a boiling point of only –19 °C (–2 °F).

VOCs are numerous, varied, and ubiquitous. They include both human-made and naturally occurring chemical compounds. Most scents or odors are of VOCs. VOCs play an important role in communication between plants, and messages from plants to animals. Some VOCs are dangerous to human health or cause harm to the environment. Anthropogenic VOCs are regulated by law, especially indoors, where concentrations are the highest. Harmful VOCs typically are not acutely toxic, but have compounding long-term health effects. Because the concentrations are usually low and the symptoms slow to develop, research into VOCs and their effects is difficult.

When nitrogen oxides ($NO_x$) and volatile organic compounds (VOCs) react in the presence of sunlight, ground level ozone is formed, a primary ingredient in smog. A 2005 U.S. EPA report gives road vehicles as the second largest source of VOCs in the U.S. at 26% and 19% are from non-road equipment which is mostly gasoline and diesel stations. 27% of VOC emissions are from solvents which are used in the manufacturer of paints and paint thinners and other uses. Non-road equipment is mostly gasoline and diesel stations shown in Figure 1.9.

Sources of Volatile Organic Compounds, 2005

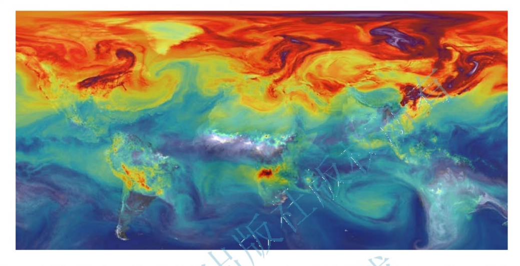
| Source | Share |
| --- | --- |
| Solvent use | 29.0% |
| On-road vehicles | 28.0% |
| Non-road equipment | 19.0% |
| Other | 13.0% |
| Industrial processes | 11.0% |

Source: EPA

**Figure 1.9　Non-road equipment is mostly gasoline and diesel station**

### 1.3.6 Carbon Dioxide ($CO_2$)

NASA is advancing new tools like the supercomputer model that created this simulation of carbon dioxide in the atmosphere to better understand what will happen to Earth's climate if the land and ocean can no longer absorb nearly half of all climate-warming $CO_2$ emissions (See Figure 1.10). NASA scientists report that human-made carbon dioxide ($CO_2$) continues to increase above levels not seen in hundreds of thousands of years: currently, about half of the carbon dioxide released from the burning of fossil fuels remains in the atmosphere and is not absorbed by vegetation and the oceans.





【参考图文】

**Figure 1.10 Carbon dioxide in Earth's atmosphere if *half* of global-warming emissions are *not* absorbed. (NASA simulation; 9 November 2015)**



Carbon dioxide is a greenhouse gas. Motor vehicle $CO_2$ emissions are part of the anthropogenic contribution to the growth of $CO_2$ concentrations in the atmosphere which is causing climate change. Motor vehicles are calculated to generate about 20% of the European Union's man-made $CO_2$ emissions, with passenger cars contributing about 12%. European emission standards limit the $CO_2$ emissions of new passenger cars and light vehicles. The European Union average new car $CO_2$ emissions figure dropped by 5.4% in the year to the first quarter of 2010, down to 145.6 g/km. At present, Volkswagen offer 245 models with $CO_2$ emissions of less than 120 g/km. By 2020, the company will reduce the average $CO_2$ emissions of its European new car fleet to 95 g/km, as shown in Figure 1.11. And the company will take the powertrain technologies to minimize greenhouse gas emission, as shown in Figure 1.12.

At present, Volkswagen offers 245 models with $CO_2$ emissions of less than 120 g/km, By 2020, the company will reduce the average $CO_2$ emissions of its European new car fleet to 95 g/km.

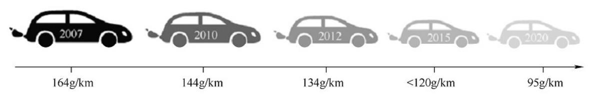



**Figure 1.11 $CO_2$ Emissions**

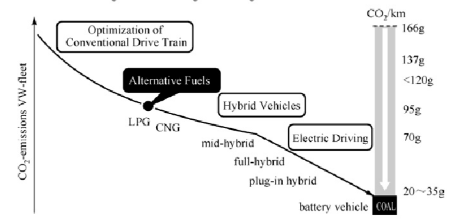



**Figure 1.12 Powertrain technologies**

## 1.4 Pollution Effects



Air pollution associated with transit fuels comes from several sources, including fuel production (e.g., petroleum refining or electric power generation), fuel transportation, evaporative emissions, and tailpipe emissions from transit vehicles. In communities where transit vehicles operate frequently, tailpipe emissions make the greatest impact on air quality. Exhaust tends to accumulate around localized hotspots such as transit bus depots and railroad stations.

Table 1.1 describes the four pollutants subject to U.S. EPA motor vehicle emissions standards—particulate matter (PM), oxides of nitrogen ($NO_x$), hydrocarbons (HC), and carbon monoxide (CO)—and their environmental and health effects. The table shows that PM exhaust can be toxic and that $NO_x$ and NMHC can form ground level ozone, a principal component of smog. Because of high concentrations of soot, ozone, and smog in many urban areas, these emissions are of primary concern. Diesel vehicles are not a major source of CO.

**Table 1.1 Regulated Pollutants in Diesel Exhaust and their Health and Environmental Effect**

| Pollutant | Source | Description | Environmental and Health Effects |
| --- | --- | --- | --- |
| Particulate Matter (PM) | Product of fuel or lubricating oil combustion | Tiny carbon particles (soot or smoke) with sometimes-toxic organic compounds attached | PM can affect respiratory health and carry toxic substances into the lungs and bloodstream. PM finer than 10 microns in diameter (PM10) is absorbed by the lungs causing lung damage. The core carbon of PM may not be the primary culprit of adverse health effects. Instead, compounds, when bonded to the tiniest carbon particulates, penetrate deep into the lungs and are suspected of triggering a cascade of effects in many body systems. |

续表

| Pollutant | Source | Description | Environmental and Health Effects |
|---|---|---|---|
| Oxides of Nitrogen ($NO_x$) | Reactions between oxygen and nitrogen in the engine's combustion chamber | Gases including NO (nitric oxide) and $NO_2$ (nitrogen dioxide). As emitted directly from the tailpipe, $NO_x$ consists mainly of nitric oxide (NO) (90% NO + 10% $NO_2$) although vehicles equipped with certain types of aftertreatment systems can emit as much as 35% nitrogen dioxide $NO_2$). | $NO_2$ is an oxidizing gas, which in concentrations higher than 0.2 ppm, irritates and damages lung tissue. $NO_2$ also combines with water to form nitric acid, which is damaging to plants. $NO_2$ is a precursor in the formation of ground level ozone ($O_3$) and smog and contributes to global warming. NO is non-toxic and does not promote the formation of ozone. However, NO is rapidly converted to $NO_2$ in the atmosphere. |
| Hydrocarbons (HC) and Non-Methane Hydrocarbons (NMHC) | Unburned or partially burned fuel, fuel spills | Hydrocarbons contain both reactive species, called volatile organic compounds, and non-reactive species, such as methane. | Hydrocarbons are ozone precursors. In the presence of sunlight, reactive hydrocarbons react with $NO_2$ in the atmosphere to produce ozone. Methane, the principal HC constituent in CNG engine exhaust, while not photochemically reactive, is a powerful greenhouse gas. |
| Carbon monoxide (CO) | Incomplete combustion of carbon-containing fuels | Highly toxic gas | CO is hazardous in high concentrations because it binds with hemoglobin in the blood, impairing its ability to transport oxygen to the brain and other vital organs. |



The health hazards associated with motor vehicle exhausts are particularly worrying. If you place a stationary diesel engine with the exhaust near a wall, the wall very quickly turns black with what can loosely be described as soot. Again you do not need to be a medical scientist to realize the effect that this might have on your lungs. You would need to smoke a lot of cigarettes to get the same level of deposit, and we all know the health effects of tobacco smoke. Although you do not have to stand behind diesel exhausts, you are bound to inhale a fair amount walking along a busy street and crossing the road, which often involves passing directly through vehicle exhaust.

Accepted health problems associated with car exhausts makes depressing reading and one has to wonder why society keeps quite happily emitting these substances.

New discoveries on the risks of cancer from exhaust fumes continue to emerge. Researchers in Japan have apparently isolated a compound called 3-nitrobenzanthone which is a highly potent mutagen. Clearly this is a cause for alarm. It must also be remembered that new research is constantly emerging and the overall picture may well be extremely grim. Certainly there have been large rises in asthma, many allergies and cancers that may well be linked to exhaust fumes.

The effect of carbon dioxide on the planet is another cause for alarm. The greenhouse effect of carbon dioxide is now well known. Basically, some of the short-wave radiation from the sun is absorbed by the earth and then re-emitted at a longer wavelength. This is absorbed by carbon dioxide





and other gases and then re-emitted, the downward radiation warming the surface of the earth. The atmospheric concentration of carbon dioxide has increased by about 25% over the past 100 years.

Although a warmer earth may sound appealing to those living in cold climates, there are side effects which could prove absolutely devastating. Firstly the earth relies on a reasonably set weather pattern for growing food. A change of climate in the grain growing belt of America, for example, could itself have serious consequences on food supply. Secondly the "warm up" is melting the polar ice caps and this could cause permanent flooding in low-lying areas. Bearing in mind that many major cities, London, New York, Barcelona, San Francisco, Perth (Australia) and scores of others, are built on the coast, this could have very serious repercussions throughout the world.

## 1.5 Emission Factors

Air pollutant emission factors are reported representative values that attempt to relate the quantity of a pollutant released to the ambient air with an activity associated with the release of that pollutant. These factors are usually expressed as the weight of pollutant divided by a unit weight, volume, distance, or duration of the activity emitting the pollutant (e.g., kilograms of Particulate emitted per tonne of coal burned). Such factors facilitate estimation of emissions from various sources of air pollution. In most cases, these factors are simply averages of all available data of acceptable quality, and are generally assumed to be representative of long-term averages.

There are 12 compounds in the list of persistent organic pollutants. Dioxins and furans are two of them and intentionally created by combustion of organics, like open burning of plastics. These compounds are also endocrine disruptors and can mutate the human genes.

Two photos taken in the same location in Beijing in August 2005. The photograph on the left was taken after it had rained for two days. The right photograph shows smog covering Beijing in what would otherwise be a sunny day, as shown in Figure 1.13.



**Figure 1.13 Beijing air on a 2005-day after rain (left) and a smoggy day (right)**

## 1.6 Pollution Reduction

Emission standards focus on reducing pollutants contained in the exhaust gases from vehicles as well as from industrial flue gas stacks and other air pollution exhaust sources in various large-scale industrial facilities such as petroleum refineries, natural gas processing plants, petrochemical plants and chemical production plants. However, these are often referred to as flue gases. Catalytic converters in cars intend to break down the pollution of exhaust gases using a catalyst.

One of the advantages claimed for advanced technology engines is that they produce smaller quantities of toxic pollutants (e.g. oxides of nitrogen) than petrol and diesel engines of the same power. They produce larger quantities of carbon dioxide but less carbon monoxide due to more efficient combustion.

Emissions standards continue to tighten. New bus engine standards will take effect in the 2015 model year, with 80 to 89 percent reductions in PM and HC emission limits and similar reductions for $NO_x$. Nearly all manufacturers will choose to meet $NO_x$ standard incrementally— first by meeting an interim standard. The reduction in emission limits for PM and NO in 2007 and 2010 is shown graphically in the EPA chart in Figure 1.14.



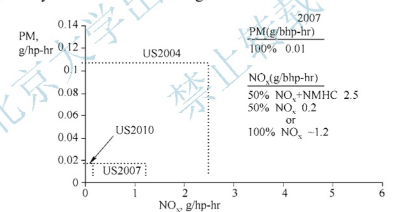



**Figure 1.14 EPA PM and $NO_x$ Emission Standards**



**Questions**

1. How will air pollution impact on the health of human beings?
2. What is the impact of vehicle emission on the environment?
3. In what way can we reduce air pollution?
4. What are the main nitrogen oxides?
5. What is volatile organic compounds?

# Chapter 2

# Mechanism on Emission Control

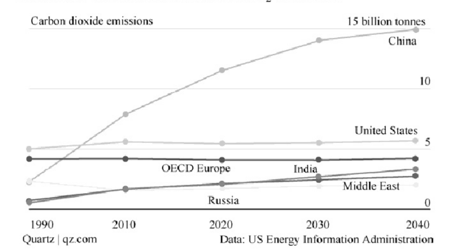





There is an increasing carbon dioxide emission in many developing countries, especially in China in the above figure. However staff estimates that the proposed regulation will reduce climate change emissions from the light duty passenger vehicle fleet by an estimated 87,700 $CO_2$-equivalent tons per day statewide in 2020 and by 155,200 $CO_2$-equivalent tons per day in 2030. This equates to an 18% reduction in climate changes emissions from the light-duty fleet in 2020 and a 27% reduction in 2030. In addition, staff estimates that the proposed regulation will reduce "upstream" smog-forming emissions of hydrocarbons and oxides of nitrogen by approximately 6 tons per day in 2020 and 10 tons per day in 2030. The $CO_2$ emission prediction is shown in Figure 2.1.

Question：What is the best method to control $CO_2$ emission?



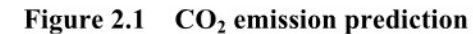
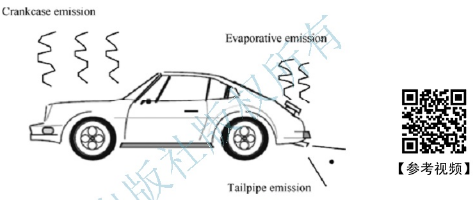



**Figure 2.1 $CO_2$ emission prediction**

# 2.1 General Principle

Exhaust gas or flue gas is emitted as a result of the combustion of fuels such as natural gas, gasoline/petrol, biodiesel blends, diesel fuel, fuel oil or coal, as shown in Figure 2.2. According to the type of engine, it is discharged into the atmosphere through an exhaust pipe, flue gas stack or propelling nozzle. It often disperses downwind in a pattern called an exhaust plume. It is a major component of motor vehicle emissions, which can also include crankcase blow-by and evaporation of unused gasoline.




【参考视频】

**Figure 2.2 The source of gasoline engine emission**



Given complete combustion, each kg of hydrocarbon fuel when completely burnt produces mainly 3.1 kg of $CO_2$ and 1.3 kg of $H_2O$. Most of the undesirable exhaust emissions are produced in minute quantities (parts per million), and these are: oxides of nitrogen, generally termed $NO_x$, unburnt hydrocarbons (HC), carbon monoxide (CO), carbon dioxide ($CO_2$), lead salts, polyaromatics, soots, aldehydes ketones and nitro-olefins. Of these, only the first three are of major significance in the quantities produced. However, concentrations in general could become heavier as increasing numbers of vehicles come onto our roads. By the end of the 1980s, $CO_2$ was beginning to cause concern, not because it is toxic but because it was suspected of facilitating the penetration of our atmosphere by ultra-violet rays emitted by the sun. Controversy has raged over lead salts, but no proof has been found that, in the quantities in which they are present in the atmosphere, they are harmful. For many years, manufacturers of catalytic converters pressed for unleaded petrol because lead deposits rapidly rendered their converters ineffective.

## 2.1.1 Measures for Controlling Emissions

### 2.1.1.1 Spark Ignition Engine

A basic essential for spark ignition engine emission control is an injection system capable of extreme accuracy in metering the fuel supply relative to the air entering the engine. All modern fuel injection systems have been developed from the outset specifically for accuracy of metering, for

minimal emissions and best fuel economy. Irregular combustion must be avoided during idling and, on the overrun, the mixture must either be totally combustible or the fuel supply totally cut off. In the latter event a smooth return to normal combustion when the throttle is opened again is essential. Idling speeds are typically 750 rev/min with automatic and 550 rev/min with manual transmission.

#### 2.1.1.2 Diesel Engine

Diesel and spark ignition engines produce the same emission. On the other hand, owing to the low volatility of diesel fuel relative to that of gasoline, evaporative emissions are not so significant. Crankcase emissions, too, are of less importance, since only pure air is compressed in the cylinder and blow-by constitutes only a minute proportion of the total combustion gases produced during the expansion stroke.

Sulphur, which plays a major part in the production of particulates and smoke emissions is present in larger proportions in diesel fuel than in petrol. This is one of the reasons why the combustion of diesel fuel produces between 5 and 10 times more solid particles than that of petrol.

Because diesel power output is governed by regulating the supply of fuel without throttling the air supply, there is excess air and therefore virtually zero CO in the exhaust under normal cruising conditions. Reduction of $NO_x$ on the other hand can be done only in an oxygen-free atmosphere.

As a diesel engine is opened up towards maximum power and torque, $NO_x$ output increases because of the higher combustion temperatures and pressures.

### 2.1.2 Reduction of Emissions: Conflicting Requirements

Measures taken to reduce $NO_x$ tend to increase the quantity of particulates and HC in the exhaust, as shown in Figure 2.3. This is primarily because, while $NO_x$ is reduced by lowering the combustion temperature, both soot and HC are burned off by increasing it. In consequence, some of the regulations introduced in Europe have placed limits on the total output of both $NO_x$ and HC, instead of on each separately, leaving manufacturers free to obtain the best compromise between the two.

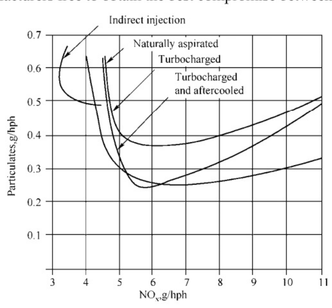



**Figure 2.3 $NO_x$ increases when measures are taken to reduce particulates in different types of engine**

The problem of emission control, however, is not so severe. Both $NO_x$ output and heat to exhaust become significant only as maximum torque and power are approached. At lighter loads, the gases tend to be cooled because of both their excess air content and the large expansion ratio of the diesel engine. Since the proportion of excess air falls as the load increases, oxidising catalysts can be used without risk of overheating, even at maximum power output.

Fuel blending and quality has a profound effect on emissions. Since fuel properties and qualities are interrelated, it is generally unsatisfactory to vary one property unilaterally. Indeed, efforts to reduce one exhaust pollutant can increase others and adversely affect other properties.

## 2.2 Oxides of Nitrogen($NO_x$)

### 2.2.1 Formation and Reactions

Oxygen and nitrogen do not react at ambient temperatures. But at high temperatures, they undergo an endothermic reaction producing various oxides of nitrogen. Such temperatures arise inside an internal combustion engine or a power station boiler, during the combustion of a mixture of air and fuel, and naturally in a lightning flash.

In atmospheric chemistry, the term $NO_x$ means the total concentration of NO and $NO_2$. During daylight, these concentrations are in equilibrium; the ratio $NO/NO_2$ is determined by the intensity of sunshine (which converts $NO_2$ to NO) and the concentration of ozone (which reacts with NO to again form $NO_2$).

The three principal reactions (the extended Zeldovich mechanism) producing thermal $NO_x$ are:

$$N_2 + O \rightarrow NO + N$$

$$N + O_2 \rightarrow NO + O$$

$$N + OH \rightarrow NO + H$$

All three reactions are reversible. Zeldovich was the first to suggest the importance of the first two reactions.

### 2.2.2 $NO_x$ from Fuel

It is estimated that transportation fuels cause 54% of the anthropogenic (i.e. human-caused) $NO_x$. The major source of $NO_x$ production from nitrogen-bearing fuels such as certain coals and oil, is the conversion of fuel bound nitrogen to $NO_x$ during combustion. During combustion, the nitrogen bound in the fuel is released as a free radical and ultimately forms free $N_2$, or NO. Fuel $NO_x$ can contribute as much as 50% of total emissions when combusting oil and as much as 80% when combusting coal.

Although the complete mechanism is not fully understood, there are two primary paths of formation. The first involves the oxidation of volatile nitrogen species during the initial stages of combustion. During the release and before the oxidation of the volatiles, nitrogen reacts to form

several intermediaries which are then oxidized into NO. If the volatiles evolve into a reducing atmosphere, the nitrogen evolved can readily be made to form nitrogen gas, rather than $NO_x$. The second path involves the combustion of nitrogen contained in the char matrix during the combustion of the char portion of the fuels. This reaction occurs much more slowly than the volatile phase. Only around 20% of the char nitrogen is ultimately emitted as $NO_x$, since much of the $NO_x$ that forms during this process is reduced to nitrogen by the char, which is nearly pure carbon.

### 2.2.3 Effects of Fuel Properties on $NO_x$

To understand the effects of fuel properties on $NO_x$ output certain basic facts must be borne in mind. First, it depends not only on the peak temperature of combustion but also on the rate of rise and fall to and from it. Secondly, the combustion temperatures depend on primarily the quantity and, to a lesser degree, the cetane number of the fuel injected.

#### 2.2.3.1 Increasing the Cetane Number

Increasing the cetane number reduces the delay period, so the fuel starts to burn earlier, so higher temperatures and therefore more $NO_x$ are generated while the burning gas is still being compressed, as shown in Figure 2.4. However, a smaller quantity of fuel is injected before combustion begins, and this, by reducing the amount of fuel burning at around TDC, reduces the peak combustion temperature. The net result of the two effects is relatively little or even no change in $NO_x$ output. An interesting feature in Figure 2.5 is the enormous difference between the $NO_x$ outputs from direct and indirect injection systems.



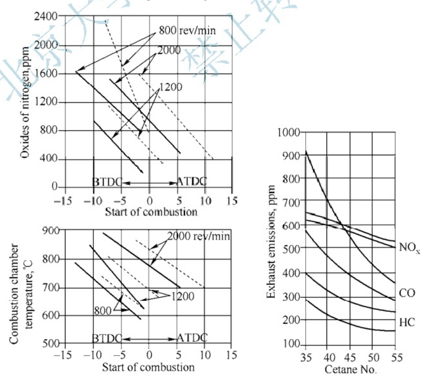



**Figure 2.4 (left) Tests by BP showing how injection timing influences combustion and therefore $NO_x$ output; (right) the influence of cetane number on the principal Emissions**

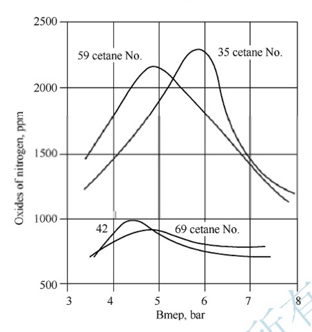



**Figure 2.5 $NO_x$ emissions with direct and indirect injection**



#### 2.2.3.2 Increasing Fuel Volatility

The popular concept that increasing fuel volatility reduces $NO_x$ is an illusion: what happens in reality is that the weight of fuel injected is reduced, and the engine is therefore de-rated. Consequently, combustion temperatures are lowered.

In the early 1990s, the overall output of $NO_x$ from the diesel engine was, on average, between 5 and 10 times that of an equivalent gasoline power unit with a catalytic converter, but this differential will be reduced as a diesel combustion control technique improves. Efforts are being made to develop catalysts suitable for diesel application, but at the time of writing no satisfactory solution has been found.

Unfortunately, most of the currently conventional methods of reducing $NO_x$ also impair efficiency and therefore increase fuel consumption and therefore the output of $CO_2$. The relationship between $NO_x$ output and fuel consumption is illustrated in Figure 2.6. In general, $NO_x$ tends to form most readily in fuel-lean zones around the injection spray.

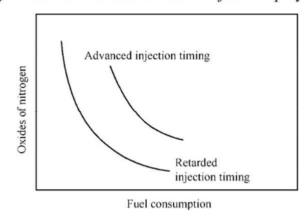



**Figure 2.6 Relationship between fuel consumption and $NO_x$ emissions with (left) and without (right) charge cooling**

#### 2.2.3.3 Exhaust Gas Recirculation

Exhaust gas recirculation displaces oxygen that otherwise would be available for combustion and thus reduces the maximum temperature. However, it also heats the incoming charge, reduces power output, causes both corrosion and wear, and leads to smoke emission at high loads. For these reasons it has to be confined to operation at moderate loads. Electronic control of EGR is therefore desirable. Fortunately, heavy commercial vehicles are driven most of the time in the economical cruising range, maximum power and torque being needed mostly for brief periods.

#### 2.2.3.4 Reduction of the Rate of Swirl

Reduction of the rate of swirl is another way of reducing the output of $NO_x$. It increases the time required for the fuel to mix with the air, and therefore reduces the concentration of oxygen around the fuel droplets. Consequently, the temperature of combustion does not rise to such a high peak. Again, however, it also reduces thermal efficiency. Moreover, unless measures, such as increasing the number of holes in the injector nozzle and reducing their diameter, are taken to shorten the lengths of the sprays, more fuel tends to be deposited on the combustion chamber walls.

#### 2.2.3.5 Delaying the Start of Injection

Delaying the start of injection has the effect of reducing peak temperatures, and therefore $NO_x$. This is because the combustion process builds up to its peak later in the cycle, when the piston is on its downward stroke and the gas is therefore being cooled by expansion. However, to get a full charge of fuel into the cylinder in the time remaining for it to be completely burnt, higher injection pressures are needed. Therefore, to avoid increasing the proportion of fuel sprayed on to the combustion chamber walls, the holes in the injector must again be smaller in diameter and larger in number.

#### 2.2.3.6 Turbocharging with Charge Cooling

Turbocharging increases the temperature of combustion by increasing both the temperature and quantity of air entering the cylinder. After-cooling, however, can help by removing the heat generated by both compression of the gas and conduction from the turbine. It also increases the density of the charge, and therefore thermal efficiency and power output. The net outcome of turbocharging with charge cooling, therefore, is generally an increase or, at worst, no reduction in thermal efficiency.



## 2.3 Unburnt Hydrocarbons

### 2.3.1 Main Reasons

Hydrocarbons (HCs) in the exhaust are the principal cause of the unpleasant smell of a diesel engine, though the lubricating oil also makes a small contribution. There are three main reasons

for this. First, at low temperatures and light loads, the mixture may be too lean for efficient burning so the precombustion processes during the ignition delay period are partially inhibited. This is why some of the mixture subsequently fails to burn.

Secondly, because of the low volatility of diesel fuel relative to petrol, and the short period of time available for it to evaporate before combustion begins, HCs are generated during starting and warming up from cold. In these circumstances, fuel droplets, together with water vapour produced by the burning of the hydrogen content of the remainder of the fuel, issue from the cold exhaust pipe in the form of what is generally termed white smoke, but which is in fact largely a mixture of fuel and water vapours. At about 10% load and rated speed, both HC and CO output are especially sensitive to fuel quality and, in particular, cetane number.

Thirdly, after cold starting and during warm-up, a higher than normal proportion of the injected fuel, failing to evaporate, is deposited on the combustion chamber walls. This further reduces the rate of evaporation of the fuel, so that it fails to be ignited before the contents of the chamber have been cooled, by expansion of the gases, to a level such that ignition can no longer occur. Similarly, the cooling effect of the expansion stroke when the engine is operating at or near full load can quench combustion in fuel-rich zones of the mixture. This is the fourth potential cause of HC emissions.

Unburnt HCs tend to become a problem also at maximum power output, owing to the difficulty under these conditions of providing enough oxygen to burn all the fuel. As fuel delivery is increased, a critical limit is reached above which first the CO and then the HC output rise steeply. Injection systems are normally set so that fuelling does not rise up to this limit, though the CO can be removed subsequently by a catalytic converter in the exhaust system.

Another potential cause of HCs is the fuel contained in the volume between the pintle needle seat and the spray hole or holes (the sac volume). After the injector needle has seated and combustion has ceased, some of the trapped fuel may evaporate into the cylinder. Finally, the crevice areas, for example, between the piston and cylinder walls above the top ring, also contain unburnt or quenched fractions of semi-burnt mixture, expanding under the influence of the high temperatures due to combustion and falling pressures during the expansion stroke, and forced out by the motions of the piston and rings. These vapours and gases find their way into the exhaust.

### 2.3.2 Ways to Reduce HC Emissions

In general, the engine designer can reduce HC emissions in three ways. First is by increasing the compression ratio; secondly, the specific loading can be increased by installing a smaller, more highly rated, engine for a given type of operation; and, thirdly, by increasing the rate of swirl both to evaporate the fuel more rapidly and to bring more oxygen into intimate contact with it.

Reduction of lubricating oil consumption is another important aim as regards not only control of HCs but also, and more importantly, particulate emissions. Whereas oil consumption at a rate of 1% of that of fuel was, until the mid-1980s, been regarded as the norm, the aim now is generally nearer to 0.2%. Using a lubricant containing a low proportion of volatile constituents helps too.

Avoidance of cylinder-bore distortion can play a significant part in the reduction of oil consumption. The piston rings tend to ride clear over and therefore fail to sweep the oil out of the pools that collect in the hollows formed by distortion of the bores, thus reducing the effectiveness of oil control. Other means of reducing contamination by lubricating oil include improving the sealing around the inlet valve stems, the use of piston rings designed to exercise better control over the thickness of the oil film on the cylinder walls and, if the engine is turbocharged, reduction of leakage of oil from the turbocharger bearings into the incoming air.

## 2.4 Carbon Monoxide



Carbon monoxide (CO) is a colorless, odorless, and tasteless gas that is slightly less dense than air. Carbon monoxide consists of one carbon atom and one oxygen atom, connected by a triple bond that consists of two covalent bonds as well as one dative covalent bond. It is the simplest oxocarbon and is isoelectronic with the cyanide anion, the nitrosonium cation and molecular nitrogen. In coordination complexes the carbon monoxide ligand is called carbonyl.

Carbon monoxide has a molar mass of 28.0, which makes it slightly lighter than air, whose average molar mass is 28.8. According to the ideal gas law, CO is therefore less dense than air.

The bond length between the carbon atom and the oxygen atom is 112.8 pm,as shown in Figure 2.7. This bond length is consistent with a triple bond, as in molecular nitrogen ($N_2$), which has a similar bond length and nearly the same molecular mass. Carbon–oxygen double bonds are significantly longer, 120.8 pm in formaldehyde, for example. The boiling point (82 K) and melting point (68 K) are very similar to those of $N_2$ (77 K and 63 K, respectively). The bond dissociation energy of 1072 kJ/mol is stronger than that of $N_2$ (942 kJ/mol) and represents the strongest chemical bond known.



【参考图文】

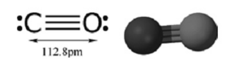



**Figure 2.7 Model(left) and Ball-and-stick model(right) of carbon monoxide**

Carbon monoxide occurs in various natural and artificial environments. Exhaust from automobiles is about 100–200 ppmv in typical concentrations per million.

Even at maximum power output, there is as much as 38% of excess air in the combustion

chamber. However, although carbon monoxide should not be formed, it may in fact be found in small quantities in the exhaust. The reason is partly that, in local areas of the combustion chamber, most of the oxygen has been consumed before injection ceases and, therefore, fuel injected into these areas cannot burn completely to $CO_2$.

## 2.5 Particulate Matter

### 2.5.1 Definition

Particulate matter (PM) or particulates is microscopic solid or liquid matter suspended in the Earth's atmosphere. The term aerosol commonly refers to the particulate/air mixture, as opposed to the particulate matter alone. Sources of particulate matter can be man-made or natural. They have impacts on climate and precipitation that adversely affect human health.

Subtypes of atmospheric particle matter include:

- ✧ Suspended particulate matter (SPM),
- ✧ Respirable suspended particle (RSP), which are particles with a diameter of 10 micrometres or less, also known as PM10,
- ✧ Fine particles with a diameter of 2.5 micrometres or less, a.k.a. PM2.5,
- ✧ Ultrafine particles, and,
- ✧ Soot.

Human activities, such as the burning of fossil fuels in vehicles, power plants and various industrial processes also generate significant amounts of particulates.

Regulations define particulates as anything that is retained, at an exhaust gas temperature of 52°C, by a filter having certain specified properties. They therefore include liquids as well as solids. Particle sizes range from 0.01 to 10 μm, the majority being well under 1.0 μm. While black smoke comprises mainly carbon, the heavier particulates comprise ash and other substances, some combined with carbon. The proportions, however, depend on types of engine, fuel and lubricant.

### 2.5.2 Control Technologies

#### 2.5.2.1 Better Atomization of the Fuel

Measures appropriate for reducing the fuel and oil content of the particulates are the same as those already mentioned in connection with HC emissions, The overall quantity of particulates can be reduced by increasing the injection pressure and reducing the size of the injector holes, to atomise the fuel better. This however, tends to increase the $NO_x$ content. Increasing the combustion temperature helps to burn the loose soot deposited on the combustion chamber walls. Various measures have been taken to increase the temperature of these particulates, though mostly only experimentally. They include insulation by introducing an air gap, or some other form of

thermal barrier, between the chamber and the remainder of the piston, and the incorporation of ceramic combustion chambers in the piston crowns.

#### 2.5.2.2 Reduction of the Sulphur Content

Reduction of the sulphur content of the fuel also reduces particulates. Although the proportion of sulphate plus water is shown in Table 2.1 as being only 2% of the total, if the insoluble sulphur compounds are added, this total becomes more like 25%. Because most measures are taken to reduce $NO_x$ increase particulates, the most appropriate solution is to use fuels of high quality, primarily having low sulphur and aromatic contents and high cetane number. The relationship between fuel quality and particulate and $NO_x$ output has been demonstrated by Volvo, as shown in Figure 2.8.

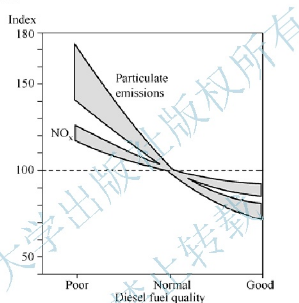



**Figure 2.8 Relationship between particulate emissions and fuel quality, as established by Volvo**



A small proportion of the particulates is ash, most of which comes from burning the lubricating oil. Reduction of sulphur in the fuel reduces the need for including, in lubricating oils, additives that neutralize the acid products of combustion; these additives are responsible for a significant proportion of the ash content.

Incidentally, sulphur compounds can also reduce the efficiency of catalytic converters for the oxidation of CO and HC. In so doing, they form hydrogen disulphide, which accounts for the unpleasant smell of the exhaust when fuels with high sulphur content are burnt in an engine having an exhaust system equipped with a catalytic converter.

#### 2.5.2.3 An Ingenious Method

An ingenious method of reducing visible particulates emitted from a turbocharged engine in a bus has been investigated by a company. Compressed air from the vehicle braking system is injected in a controlled manner into the combustion chambers to burn off the carbon. This

increases the exhaust gas energy content, and therefore compensates for turbocharger performance falling off under light load, including initially during acceleration and while gear changes are being made.

**Table 2.1 Analyses, expressed in percentages, of particulates from different types of diesel engine**

| Engine type | Fuel-derived HC | Oil-derived HC | Insoluble ash | Sulphates+water |
|---|---|---|---|---|
| Ford 1.8 DI | 15 | 13 | 70 | 2 |
| Ford 1.8 IDI | 48 | 20 | 30 | 2 |
| Average DI HD turbocharged after-cooled engine | 14 | 7 | 25 | 4 |

Note: Horrocks (Ford Motor Co.) differentiated between the carbon and other ash (at 41% and 13% respectively), making the total 44%.

## 2.6 Influence of Fuel Quality on Diesel Exhaust Emissions



How individual emissions are influenced by different fuel properties have been summarised by the UK Petroleum Industry Association as follows—

- $NO_x$ — Increases slightly with cetane number.
  Decreases as aromatic content is lowered.
- CO — No significant effects.
- HC — Decreases slightly as cetane number increases.
  Decreases with density.
  Relationship with volatility inconsistent.
- Black smoke — Increases with fuel density and decreases with aromatic content.
  Is not significantly affected by volatility.
  Increases with injection retard (e.g. for reducing $NO_x$).
- Particulates — Reduced as volatility is lowered.
  Reduced as cetane number is lowered, though inconsistently.
  Unaffected by aromatic content.
  Reduced as sulphur content is lowered.

A good quality fuel is generally regarded as one having a cetane number of 50 and a sulphur content of no greater than 0.05%.

In Sweden, Volvo have shown that by bringing the sulphur content down from 0.2 to 0.05% particulate emissions can be reduced by up to 20% and $NO_x$ is also reduced. Furthermore, ignoring the effect of the tax on fuel prices, the cost of such a reduction is only about 2 pence per gallon whereas to obtain a commensurate improvement by reducing the aromatic content and increasing the cetane number would cost about 22 pence per gallon.

## 2.7 Black Smoke

The effect of sulphur on the formation of particulates has been discussed in Section 2.5. Other factors include volatility and cetane number. As regards visibility, however, the carbon is much more important. Suggestions that volatility influences black smoke are without foundation. Smoke is reduced with increasing volatility for two reasons: first is the correspondingly falling viscosity; second the associated rising API gravity of the fuel. A consequence of the first is increased leakage of fuel through the clearances around both the pumping elements and the injector needles and, of the second, the weight of the fuel injected falls. Therefore, for any given fuel pump delivery setting, the power output decreases with increasing volatility. In fact, the real influence of volatility depends on an extremely complex combination of circumstances, and varies with factors such as speed, load and type of engine.

The reason is that each engine is designed to operate at maximum efficiency over a given range of speeds and loads with a given grade of fuel. Therefore, at any given speed and load, a change of fuel might increase the combustion efficiency, yet at another speed and load the same change might reduce it. This is because a certain weight of fuel is required to produce a given engine power output, so if the API gravity is increased, a commensurately larger volume of fuel must be supplied, and this entails injection for a longer period which, for any given engine operating condition could have either a beneficial or detrimental effect on combustion efficiency. Similarly, the resultant change in droplet size and fuel penetration relative to the air swirl could have either a beneficial or detrimental effect.

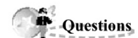
The reason why the cetane number does not have a significant effect on the output of black smoke is simple. It is that smoke density is largely determined during the burning of the last few drops of fuel to be injected into the combustion chamber.



## 2.8 White Smoke

White smoke is a mixture of partially vaporised droplets of water and fuel, the former being products of combustion and the latter arising because the temperature of the droplets fails to rise to that needed for ignition. It can be measured by passing the exhaust through a box, one side of which is transparent and the other painted matt black. A beam of light is directed through the transparent wall on to the matt black surface. If there is no white smoke, no light is reflected back to a sensor alongside the light source; the degree of reflection therefore is a function of the

density of the white smoke. For testing fuels, the criterion is the time taken, after starting from a specified low temperature, for the smoke level to reduce to an acceptable level. After starting at 0°C, satisfactory smoke levels are generally obtainable with a Diesel Index of 57 and a cetane number of 53.5.




1. What is the effects of fuel properties on $NO_x$ ?
2. What is the main approaches to reduce HC emissions ?
3. What are the influence of fuel quality on diesel exhaust emissions ?
4. What is black smoke ?
5. What is white smoke ?

# Chapter 3

# Electric Vehicles




In January 1990, General Motors' President introduced its EV concept two-seater, the "Impact", at the Los Angeles Auto Show. That September, the California Air Resources Board mandated major-automaker sales of EVs, in phases starting in 1998. From 1996 to 1998 GM produced 1117 EV1s, as shown in Figure 3.1, 800 of which were made available through three-year leases.




【参考视频】



**Figure 3.1 General Motors EV1 electric car (1996-1998), story told in movie "Who Killed the Electric Car?"**

Chrysler, Ford, GM, Honda, Nissan and Toyota also produced limited numbers of EVs for

California drivers. In 2003, upon the expiration of GM's EV1 leases, GM crushed them. The crushing has variously been attributed to:

✧ the auto industry's successful federal court challenge to California's zero-emissions vehicle mandate,

✧ a federal regulation requiring GM to produce and maintain spare parts for the few thousands EV1s and

✧ the success of the oil and auto industries' media campaign to reduce public acceptance of EVs.

A movie made on the subject in 2005–2006 was titled "Who Killed the Electric Car?" The film explores the roles of automobile manufacturers, oil industry, the U.S. government, batteries, hydrogen vehicles, and consumers, and each of their roles in limiting the deployment and adoption of this technology.

Question: What do you learn from the example?

## 3.1 Background

### 3.1.1 Definition

Mankind is becoming increasingly concerned about the damage it is causing to the environment, and electric vehicles are perceived to play a part in redressing the balance. It is therefore important that the environmental impact of electric vehicles is thoroughly understood.

Government regulations like the 130-g/km (and future planned 95-g/km) $CO_2$ average emission limits for car manufacturers in Europe are also catalysts behind new electrified transportation alternatives. With the adoption of more electronics, vehicles become safer, exhibit higher performance, and are more efficient.

Electric transportation is a key element within the overall renewable energy landscape. Energy for charging is expected to come from renewable sources like wind-, solar- or water-powered plants. Home and public charging stations will also become more prevalent and can take advantage of off-peak charging (nighttime) and green energy sources such as wind.

An electric vehicle (EV), also referred to as an electric drive vehicle, uses one or more electric motors or traction motors for propulsion. An electric vehicle may be powered through a collector system by electricity from off-vehicle sources, or may be self-contained with a battery or generator to convert fuel to electricity. EVs include road and rail vehicles, surface and underwater vessels, electric aircraft and electric spacecraft.

EVs first came into existence in the mid-19th century, when electricity was among the preferred methods for motor vehicle propulsion, providing a level of comfort and ease of operation that could not be achieved by the gasoline cars of the time. The internal combustion

engine (ICE) has been the dominant propulsion method for motor vehicles for almost 100 years, but electric power has remained commonplace in other vehicle types, such as trains and smaller vehicles of all types.

Ultimately electric vehicles may be of substantial benefit, reducing harmful emissions. There is considerable misunderstanding at present as to precisely why electric vehicles can be of benefit, and the extent of that benefit. Firstly, it must be remembered that energy has to come from somewhere, normally power stations; it does not just appear. A key part of the consideration of the environmental impact of vehicles is the so-called "well to wheels" analysis, where the pollution of all parts of the energy cycle in the use of a vehicle is considered, not just the vehicle itself.

A second point to be borne in mind is that internal combustion engine vehicles can be run entirely by sustainable fuels, as the Brazilian programme of using ethanol made from sugar cane has proved. Internal combustion engines could also be made to run with virtually zero emissions, burning hydrogen for example and thus giving an exhaust gas of (almost) just water and air. Perhaps fortunately, it is becoming easier and more efficient to use fuel cells, and electricity for charging batteries can be derived from renewable sources.

A third aspect is how the availability of electric vehicles could move people towards more environmentally responsible modes of transport. For example, if electric bicycles worked well, and were widely available, could this persuade some people to abandon their private cars, which generate considerable pollution whatever their power source?



### 3.1.2 Vehicle Pollution

There are two main problems caused by conventional vehicles. Firstly they ruin the immediate environment with noise and pollutants. Secondly they burn irreplaceable fossil fuels producing carbon dioxide which is a major cause of global warming and climate change.

One significant problem with internal combustion engine vehicles in slow traffic is that fuel consumption rises very dramatically as vehicles crawl along at slow speeds and pollution gets considerably worse. This is illustrated in Figure 3.2. With electric vehicles there will be a small decrease in efficiency of the electric motor when used at low speeds but the efficiency of batteries such as lead acid increases resulting in a fairly steady efficiency across the speed range. In cities such as London and Tokyo the average speeds are normally less than 15 kph and in rush hour are considerably less.

The simplest way of eliminating these problems from town and city streets is to enforce zero emission vehicles into the towns and cities by legislation or other means. Conventional internal combustion vehicles ruin the environment in their vicinity particularly in towns and cities.

The simplest way of creating zero emission vehicles is to adopt electric vehicles, or at least hybrid vehicles which solely run on electricity when in the town and city environment. However, the total pollution impact of vehicles and their energy use cannot be ignored.

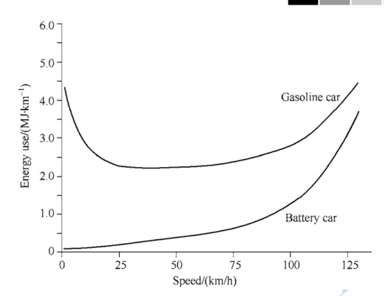



**Figure 3.2 Indicative energy use for IC engine and battery powered cars. Obviously the precise figures vary very greatly with size and design of vehicle. These figures are *not* the whole well-to-wheel energy figures, but just the tank-to-wheel or battery-to-wheel figures**



## 3.2 Electric Vehicle Types

It is generally possible to equip any kind of vehicle with an electric powertrain. Electric vehicles include battery electric vehicles, plug-in hybrid electric vehicles, and fuel cell vehicles.

- ✧ BEVs(Battery Electric Vehicles)
- ✧ PHEVs(Plug-in Hybrid Electric Vehicles)
- ✧ FCVs(Fuel Cell Vehicles)

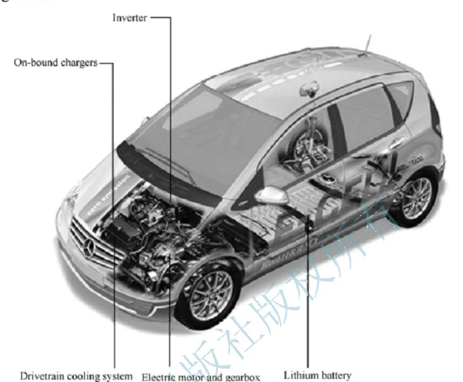
HEVs(Hybrid Electric Vehicles) have an electric motor and battery, but derive all their power from gasoline or diesel and can't be recharged by plugging in. Because of this, HEVs aren't considered electric vehicles ("EVs") but energy-saving vehicles.

### 3.2.1 Battery Electric Vehicles

A battery electric vehicle (BEV) is a type of electric vehicle (EV) that uses chemical energy stored in rechargeable battery packs. BEVs use electric motors and motor controllers instead of internal combustion engines (ICEs) for propulsion, as shown in Figure 3.3.

A battery-only electric vehicle (BOEV) or all-electric vehicle derives all its power from its battery packs and thus has no internal combustion engine, fuel cell, or fuel tank. BEVs include bicycles, scooters, skateboards, rail cars, watercraft, forklifts, buses, trucks and cars. Battery electric bus by BYD in the Nether-land is shown in Figure 3.4. Since the introduction of the all-electric Nissan Leaf (as shown in Figure 3.5,) in December 2010, about 1 million highway legal plug-in electric vehicles have been sold worldwide by mid-September 2015, of which about 620,000 are all-electric passenger cars and light-duty trucks. The best-selling all-electric car in

history is the Nissan Leaf, with sales of 200,000 units worldwide by early December 2015, followed by the Tesla Model S, with global sales of 100,000 units also by early December 2015, as shown in Figure 3.6.




【参考视频】

Figure 3.3　Battery Electric Vehicles




Figure 3.4　Battery electric bus by BYD in the Netherlands



Figure 3.5　Nissan Leaf



**Figure 3.6 The Tesla Model S is the world's second best selling all-electric car, with global sales of about 100,000 units by early December 2015**

Battery powered cars had primarily used lead-acid batteries and NiMH batteries. Lead-acid batteries' recharge capacity is considerably reduced if they're discharged beyond 75% on a regular basis, making them a less-than-ideal solution. NiMH batteries are a better choice, but are considerably more expensive than lead-acid. Lithium-ion battery powered vehicles such as the Venturi Fetish and the Tesla Roadster have recently demonstrated excellent performance and range, but they remain expensive, nevertheless is used in most mass production models launched since December 2010.

Most electric vehicles use lithium-ion batteries. Lithium-ion batteries have higher energy density, longer life span and higher power density than most other practical batteries, as shown in Figure 3.7. Complicating factors include safety, durability, thermal breakdown and cost. Lithium-ion batteries should be used within safe temperature and voltage ranges in order to operate safely and efficiently. Increasing the battery's lifespan decreases effective costs. One technique is to operate a subset of the battery cells at a time and switching these subsets.



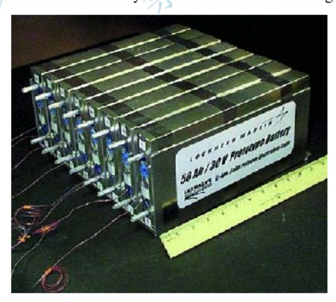



**Figure 3.7 75 watt-hour/kilogram lithium ion polymer battery prototypes. Newer Li-poly cells provide up to 130 Wh/kg and last through thousands of charging cycles.**

### 3.2.2 Plug-in Hybrid Electric Vehicles

A plug-in electric vehicle (PEV) is any motor vehicle that can be recharged from any external source of electricity, such as wall sockets, and the electricity stored in the rechargeable battery packs drives or contributes to drive the wheels, as shown in Figure 3.8. PEV is a subcategory of electric vehicles that includes all-electric or battery electric vehicles (BEVs), plug-in hybrid vehicles(PHEVs), and electric vehicle conversions of hybrid electric vehicles and conventional internal combustion engine vehicles.

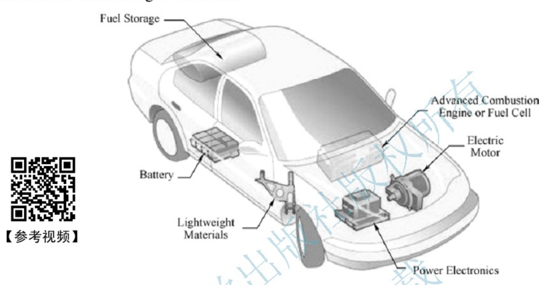



**Figure 3.8 plug-in electric vehicle**



By mid-September 2015, over one million highway-capable plug-in electric passenger cars and light utility vehicles have been sold worldwide. By early December 2015 the world's top selling plug-in electric cars are the Nissan Leaf, with global sales of 200,000 units, followed by the Chevrolet Volt plug-in hybrid (as shown in Figure 3.9).



**Figure 3.9 The Chevrolet Volt/ plug-in hybrid.**

### 3.2.3 Hydrogen Fuel Cell Vehicles

Hydrogen fuel cell vehicles (FCVs) as shown in Figure 3.10. Have a significant potential to reduce emissions from the transportation sector, because they do not emit any greenhouse gases (GHGs) during vehicle operation. Their lifecycle GHG emissions depend on how the hydrogen fuel is made.

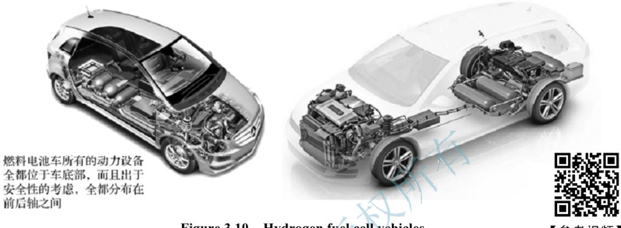



**Figure 3.10 Hydrogen fuel cell vehicles**

【参考视频】

A hydrogen car is an automobile which uses hydrogen as its primary source of power for locomotion, as shown in Figure 3.11. These cars generally use the hydrogen in one of two methods: combustion or fuel-cell conversion. In combustion, the hydrogen is "burned" in engines in fundamentally the same method as traditional gasoline cars. In fuel-cell conversion, the hydrogen is turned into electricity through fuel cells which then powers electric motors. With either method, the only byproduct from the spent hydrogen is water, however during combustion with air, $NO_x$ can be produced.






【参考视频】

**Figure 3.11 The Hyundai ix35 FCEV was release for leasing in the U.S. in 2014**

A small number of prototype hydrogen cars currently exist, and a significant amount of research is underway to make the technology more viable. The common internal combustion engine, usually fueled with gasoline (petrol) or diesel liquids, can be converted to run on gaseous hydrogen. Figure 3.12 is a hydrogen fueling station in california. However, the most efficient use of hydrogen involves the use of fuel cells and electric motors instead of a traditional engine. Hydrogen reacts with oxygen inside the fuel cells, which produces electricity to power the motors.

One primary area of research is hydrogen storage, to try to increase the range of hydrogen vehicles while reducing the weight, energy consumption, and complexity of the storage systems. Two primary methods of storage are metal hydrides and compression. Some believe that hydrogen cars will never be economically viable and that the emphasis on this technology is a diversion from the development and popularization of more efficient hybrid cars and other alternative technologies. The Hyundai ix35 FCEV fuel cell vehicle is available for lease in the U.S in 2014, a total of 54 units were leased.




**Figure 3.12　Hydrogen fueling station in California**



## 3.3　Properties of EVs

### 3.3.1　Energy Sources

Although EVs have few direct emissions, all rely on energy created through electricity generation, and will usually emit pollution and generate waste, unless it is generated by renewable source power plants. Since EVs use whatever electricity is delivered by their electrical utility/grid operator, EVs can be made more or less efficient, polluting and expensive to run, by modifying the electrical generating stations. This would be done by an electrical utility under a government energy policy, in a timescale negotiated between utilities and government.

Fossil fuel vehicle efficiency and pollution standards take years to filter through a nation's fleet of vehicles. New efficiency and pollution standards rely on the purchase of new vehicles, often as the current vehicles already on the road reach their end-of-life. Only a few nations set a retirement age for old vehicles, such as Japan or Singapore, forcing periodic upgrading of all vehicles already on the road.

EVs will take advantage of whatever environmental gains happen when a renewable energy generation station comes online; a fossil-fuel power station is decommissioned or upgraded. Conversely, if government policy or economic conditions shifts generators back to use more polluting fossil fuels and internal combustion engine vehicles (ICEVs), or more inefficient sources,

the reverse can happen. Even in such a situation, electrical vehicles are still more efficient than a comparable amount of fossil fuel vehicles. In areas with a deregulated electrical energy market, an electrical vehicle owner can choose whether to run his electrical vehicle off conventional electrical energy sources, or strictly from renewable electrical energy sources (presumably at an additional cost), pushing other consumers onto conventional sources, and switch at any time between the two.

### 3.3.2 Charging

#### 3.3.2.1 Grid capacity

If a large proportion of private vehicles were to convert to grid electricity it would increase the demand for generation and transmission, and consequent emissions. However, overall energy consumption and emissions would diminish because of the higher efficiency of EVs over the entire cycle. In the USA it has been estimated there is already nearly sufficient existing power plant and transmission infrastructure, assuming that most charging would occur overnight, using the most efficient off-peak base load sources.

#### 3.3.2.2 Charging stations

An electric vehicle charging station, as shown in Figure 3.13, also called EV charging station, electric recharging point, charging point, charge point and EVSE (Electric Vehicle Supply Equipment), is an element in an infrastructure that supplies electric energy for the recharging of electric vehicles, such as plug-in electric vehicles, including electric cars, neighborhood electric vehicles and plug-in hybrids.

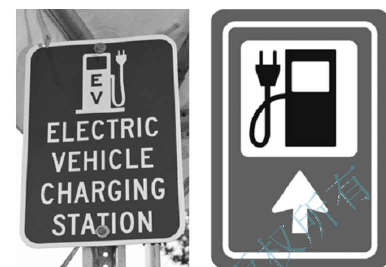





**Figure 3.13 Charging stations for electric vehicles**

EVs typically charge from conventional power outlets or dedicated charging stations, a process that typically takes hours, but can be done overnight and often gives a charge that is sufficient for normal everyday usage.

Many charging stations are on-street facilities provided by electric utility companies or located at retail shopping centers and operated by many private companies. These charging stations provide one or a range of heavy duty or special connectors that conform to the variety of electric charging connector standards. The traffic sign is shown in Figure 3.14.




【参考视频】

**Figure 3.14　U.S. (left) and European(right) traffic sign used for EV charging station**

### 3.3.2.3　Battery swapping

Instead of recharging EVs from electric socket, batteries could be mechanically replaced on special stations in a couple of minutes (battery swapping).

Batteries with greatest energy density such as metal-air fuel cells usually cannot be recharged in purely electric way. Instead, some kind of metallurgical process is needed, such as aluminum smelting and similar.

Silicon-air, aluminum-air and other metal-air fuel cells look promising candidates for swap batteries. Any source of energy, renewable or non-renewable, could be used to remake used metal-air fuel cells with relatively high efficiency. Investment in infrastructure will be needed. The cost of such batteries could be an issue, although they could be made with replaceable anodes and electrolyte.

### 3.3.2.4　Charging time

The battery capacity of a fully charged electric vehicle from electric vehicle automakers (such as Nissan) is about 20 kWh, providing it with an electrical autonomy of about 100 miles. Tesla Motors released their Model S with battery capacities of 60 kWh and 85 kWh with the latter having an estimated range of approximately 480 km. Plug-in hybrid vehicles have capacity of roughly 3 to 5 kWh, for an electrical autonomy of 20 to 40 kilometres, but the gasoline engine ensures the full autonomy of a conventional vehicle.

As the electric-only autonomy is still limited, the vehicle has to be charged every two or three days on average. In practice, drivers plug in their vehicles each night, thus starting each day with a full charge.

### 3.3.3 Other In-development Technologies

- ✧ Conventional electric double-layer capacitors are being worked to achieve the energy density of lithium-ion batteries, offering almost unlimited lifespans and no environmental issues. Electric double-layer capacitors could improve lithium-ion energy density several times over if they can be produced. Lithium-sulphur batteries offer 250 Wh/kg. Sodium-ion batteries promise 400 Wh/kg with only minimal expansion/contraction during charge/discharge and a very high surface area.
- ✧ There is a growing concern about the safety of EVs, given the demonstrated tendency of the lithium-ion battery, most promising for EV use because of its high energy density, to overheat, possibly leading to fire or explosion, especially when damaged in a crash.

## 3.4 Advantages and Disadvantages of EVs



### 3.4.1 Environmental Impacts

EVs release no tail pipe air pollutants at the place where they are operated. They also typically generate less noise pollution than an internal combustion engine vehicle, whether at rest or in motion. The energy that electric and hybrid cars consume is usually generated by means that have environmental impacts. Nevertheless, adaption of EVs would have a significant net environmental benefit, except in a few countries that continue to rely on older coal fired power plants for the bulk of their electricity generation throughout the life of the car.

There is special kind of electric vehicles that help lower the pollution created by vehicles. These vehicles are powered by electricity—usually charged batteries—rather than oil or gas and currently heavily promoted by the government to facilitate environmental and vehicle management issues. Electric motors don't require oxygen, unlike internal combustion engines; this is useful for submarines and for space rovers.

### 3.4.2 Mechanical Impacts

Electric motors (as shown in Figure 3.15) are mechanically very simple and often achieve 90% energy conversion efficiency over the full range of speeds and power output and can be precisely controlled. They can also be combined with regenerative braking systems that have the ability to convert movement energy back into stored electricity. This can be used to reduce the wear on brake systems (and consequent brake pad dust) and reduce the total energy requirement of a trip. Regenerative braking is especially effective for start-and-stop city use.

They can be finely controlled and provide high torque from rest, unlike internal combustion engines, and do not need multiple gears to match power curves. This removes the need for gearboxes and torque converters.


【参考图文】



**Figure 3.15　Tesla Model S chassis with drive motor**

EVs provide quiet and smooth operation and consequently have less noise and vibration than internal combustion engines. While this is a desirable attribute, it has also evoked concern that the absence of the usual sounds of an approaching vehicle poses a danger to blind, elderly and very young pedestrians. To mitigate this situation, automakers and individual companies are developing systems that produce warning sounds when EVs are moving slowly, up to a speed when normal motion and rotation (road, suspension, electric motor, etc.) noises become audible.

### 3.4.3　Energy Efficiency

EV "tank-to-wheels" efficiency is about a factor of 3 higher than internal combustion engine vehicles. Energy is not consumed while the vehicle is stationary, unlike internal combustion engines which consume fuel while idling. However, looking at the well-to-wheel efficiency of EVs, their total emissions, while still lower, are closer to an efficient gasoline or diesel in most countries where electricity generation relies on fossil fuels.

Well-to-wheel efficiency of an EV has less to do with the vehicle itself and more to do with the method of electricity production. A particular EV would instantly become twice as efficient if electricity production were switched from fossil fuel to a wind or tidal primary source of energy. Thus, when "well-to-wheels" is cited, one should keep in mind that the discussion is no longer about the vehicle, but rather about the entire energy supply infrastructure—in the case of fossil fuels this should also include energy spent on exploration, mining, refining, and distribution.



### 3.4.4　Cost of Recharge

The reality is that the cost of operating an EV varies wildly depending on the part of the world in which the owner lives. In some locations an EV costs less to drive than a comparable gas-powered vehicle, as long as the higher initial purchase-price is not factored in (i.e. a pure comparison of gasoline cost to electricity cost). In the USA, however, in states which have a tiered electricity rate schedule, "fuel" for EVs today costs owners significantly more than fuel for a comparable gas-powered vehicle. It is dramatically more expensive to drive a pure-EV than it is to drive a traditional pure-gas powered vehicle.

### 3.4.5 Stabilization of the Grid

Since EVs can be plugged into the electric grid when not in use, there is a potential for battery powered vehicles to even cut the demand for electricity by feeding electricity into the grid from their batteries during peak use periods (such as midafternoon air conditioning use) while doing most of their charging at night, when there is unused generating capacity. This vehicle-to-grid (V2G) connection has the potential to reduce the need for new power plants, as long as vehicle owners do not mind reducing the life of their batteries, by being drained by the power company during peak demand.

Furthermore, our current electricity infrastructure may need to cope with increasing shares of variable-output power sources such as windmills and PV solar panels. This variability could be addressed by adjusting the speed at which EV batteries are charged, or possibly even discharged.

Some concepts see battery exchanges and battery charging stations, much like gas/petrol stations today. Clearly these will require enormous storage and charging potentials, which could be manipulated to vary the rate of charging, and to output power during shortage periods, much as diesel generators are used for short periods to stabilize some national grids.

### 3.4.6 Heating of EVs

In cold climates, considerable energy is needed to heat the interior of a vehicle and to defrost the windows. With internal combustion engines, this heat already exists as waste combustion heat diverted from the engine cooling circuit. This process offsets the greenhouse gases' external costs. If this is done with battery EVs, the interior heating requires extra energy from the vehicles' batteries. Although some heat could be harvested from the motor(s) and battery, their greater efficiency means there is not as much waste heat available as from a combustion engine.

However, for vehicles which are connected to the grid, battery EVs can be preheated, or cooled, with little or no need for battery energy, especially for short trips.

Newer designs are focused on using super-insulated cabins which can heat the vehicle using the body heat of the passengers. This is not enough, however, in colder climates as a driver delivers only about 100W of heating power. A heat pump system, capable of cooling the cabin during summer and heating it during winter, seems to be the most practical and promising way of solving the thermal management of the EV.

## 3.5 Hydrogen Fuel Cell Vehicles

### 3.5.1 The Benefits of Hydrogen-Powered Vehicles

Hydrogen FCVs are considered one of several possible long-term pathways for low-carbon passenger transportation (other options include vehicles powered by electricity and/or biofuels).

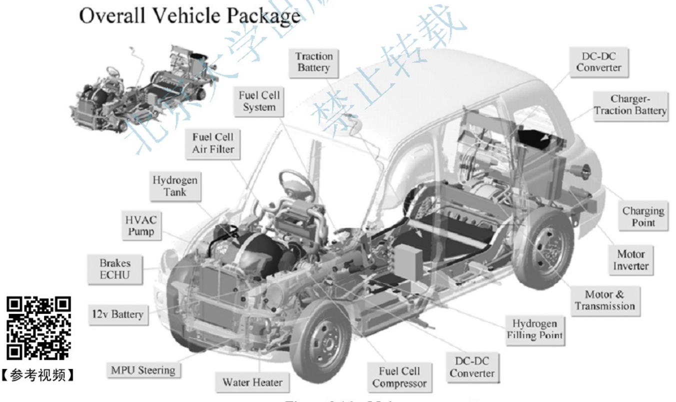
The benefits of hydrogen-powered vehicles include the following:

- ✧ High energy efficiency of fuel cell drivetrains, which use 40 to 60 percent of the energy available from hydrogen, compared with internal combustion engines, which currently use only about 20 percent of the energy from gasoline;
- ✧ Diverse methods by which hydrogen can be produced;
- ✧ Unlike all-electric vehicles(EVs), comparable vehicle range and refueling time to gasoline vehicles;
- ✧ Similar to EVs, quick starts due to high torque from the electric motor and low operating noise; and
- ✧ Lack of any greenhouse gas (GHG) emissions and few other air pollutants during vehicle operation and the potential for very low or no upstream GHG emissions associated with hydrogen fuel production.

### 3.5.2 Major Components

FCVs resemble normal gasoline or diesel-powered vehicles from the outside. Similar to EVs, they use electricity to power a motor that propels the vehicle. Yet unlike EVs, which are powered by a battery, FCVs use electricity produced from on-board fuel cells to power the vehicle. An FCV includes four major components (as shown in Figure 3.18):






【参考视频】

**Figure 3.16 Major components**

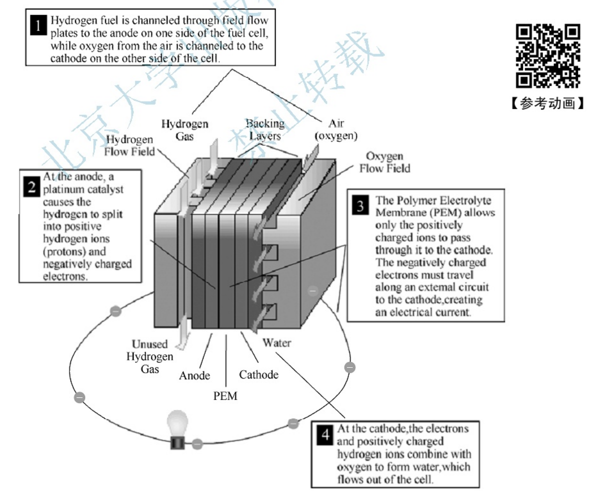
#### 3.5.2.1 Fuel cell stack

The fuel cell is an electrochemical device that produces electricity using hydrogen and

oxygen. In very simple terms, a fuel cell uses a catalyst to split hydrogen into protons and electrons, the electrons then travel through an external circuit (thus creating an electric current), and the hydrogen-ions and electrons react with oxygen to create water.

A fuel cell is composed of an electrolyte, placed between an anode (a negative electrode) and a cathode (a positive electrode), with bipolar plates on either side. The most common type of fuel cell used in FCVs is polymer electrolyte membrane (PEM) in the Figure 3.17. A fuel cell works as follows:

- ✧ First, the hydrogen gas flows to the anode. Here, a platinum catalyst is used to separate the hydrogen molecule into positive hydrogen ions (protons) and negatively charged electrons.
- ✧ The PEM allows only the protons to pass through to the cathode, while the electrons travel through an external circuit to the cathode. The flow of electrons through this circuit creates the electric current (or electricity) used to power the vehicle motor.
- ✧ On the other side of the cell, oxygen gas, usually drawn from the outside air, flows to the cathode.
- ✧ When the electrons return from the external circuit, the positively charged hydrogen-ions and electrons react with oxygen in the cathode to form water, which then flows out of the cell. The cathode also uses a platinum catalyst to enable this reaction.




【参考动画】

**Figure 3.17 PEM fuel cell**

#### 3.5.2.2 Hydrogen storage tank

Instead of a gasoline or diesel tank, an FCV has a hydrogen storage tank, as shown in Figure 3.18. The hydrogen gas must be compressed at extremely high pressure at 5,000 to 10,000 pounds per square inch (psi) to store enough fuel to obtain adequate driving range. In comparison, compressed natural gas (CNG) vehicles use high-pressure tanks at only 3,000 to 3,600 psi.

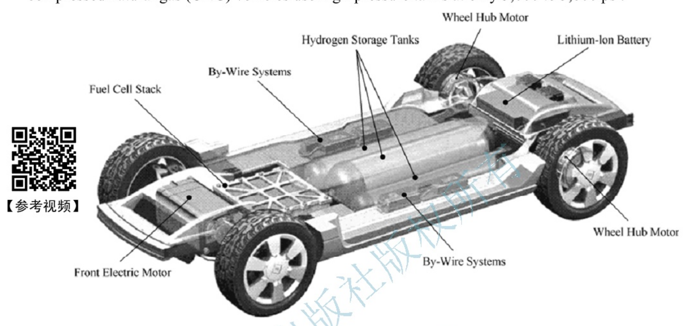



**Figure 3.18 FCV chassis**



#### 3.5.2.3 Electric motor and power control unit

The power control unit governs flow of electricity in the vehicle. By drawing power from either the battery or the fuel cell stack, it delivers electric power to the motor, which then uses the electricity to propel the vehicle.

#### 3.5.2.4 Battery

Like HEVs, FCVs also have a battery that stores electricity generated from regenerative braking, increasing the overall efficiency of the vehicle. The size and type of these batteries, similar to those in HEVs, will depend on the “degree of hybridization” of the vehicle, i.e., how much of the power to propel the vehicle comes from the battery and how much comes from the fuel cell stack.

### 3.5.3 Obstacles to Further Development

#### 3.5.3.1 Fuel cell technology

Significant improvements in fuel cell durability and costs are needed for FCVs to achieve commercial success. These are limited by the properties of catalysts and available membrane materials. Targets set by industry aim for an operating life of 5,000–5,500 hours and 17,000 start/stop cycles for a fuel cell system. Achieving this target would allow FCVs to be competitive

with conventional vehicles in terms of durability. To date, automotive fuel cells have not demonstrated this level of reliability.

#### 3.5.3.2 On-board hydrogen storage

Although hydrogen contains three times more energy per weight than gasoline, it contains one-third of the energy per volume. Storing enough hydrogen to obtain a vehicle range of 300 miles would require a very large tank, too large for a typical car. Currently the most cost-effective option is using high-pressure tanks, yet these systems are large, heavy, and too costly to make FCVs cost-competitive. Other options include storing hydrogen in metal- or chemical-hydrides or producing hydrogen onboard.

#### 3.5.3.3 Hydrogen production

Hydrogen can be produced using a variety of methods, with substantially different GHG footprints. For FCVs to be competitive as a GHG-reduction strategy, more development of low-cost and low-GHG hydrogen production methods will be needed.

#### 3.5.3.4 Distribution infrastructure

There is currently no national system to deliver hydrogen from production facilities to filling stations, similar to that for diesel or gasoline. A completely new distribution infrastructure will be required to allow mass market penetration of FCVs.

#### 3.5.3.5 Vehicle cost

For FCVs to become cost-competitive, high production volumes are needed to make vehicle plus fuel costs less than those for a gasoline vehicle. In the Figure 3.19, although the cost of fuel cells has decreased significantly, the cost for a fuel cell system is almost double that of an internal combustion engine. Overall vehicle costs are also substantially higher than that for conventional vehicles.



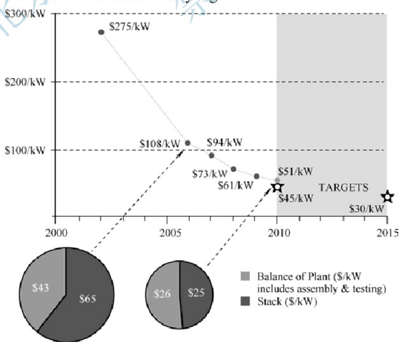



**Figure 3.19 Reduction in Fuel Cell System Cost**

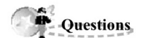
#### 3.5.3.6 Competition with other technologies

There is a range of potential alternative technologies available for use in the transportation sector, including higher efficiency gasoline- and diesel-powered vehicles, biofuels, HEVs, and PEVs. To be competitive with these technologies, FCVs will have to improve in terms of performance, durability, and cost.

#### 3.5.3.7 Safety and public acceptance

Safety concerns include the pressurized storage of hydrogen on-board vehicles. Hydrogen gas is odorless, colorless, and tasteless, and thus unable to be detected by human senses. Unlike natural gas, hydrogen cannot be odorized to aid human detection; furthermore, current odorants contaminate fuel cells and impair cell functioning. It is also more combustible than gasoline, although flames produce lower radiant heat which limits the chance of secondary fires. Improved on-board storage will reduce safety concerns.

Consumers will have to become familiar with and embrace fuel cell technology before FCVs can become widespread. In addition, the durability and reliability of fuel cells will need to be comparable to the lifetime of a conventional passenger vehicle, approximately 14 years.



### Questions

1. What are the advantages and disadvantages of electric vehicles?
2. What role do electric vehicles play in the environmental protection?
3. What are the electric vehicle types ?
4. What are the benefits of hydrogen-powered vehicles ?
5. What are the major components of a hydrogen fuel cell vehicle?

# Chapter 4

# Hybrid and Plug-in Hybrid Electric Vehicle




What could be the possible number of PHEVs on the road in 2018 in the VACAR (South Carolina, North Carolina, and much of Virginia) region? First, what is the projected market share and how will this grow? According to the Duvall report, PHEV-20 vehicles have a base case market potential of over 25% of sales for the entire car and light-truck market regardless of commute distance. Of course, the actual penetration will depend on a number of factors that are unknown yet, but as an assumption we used a gradual ramp-up of market share from 0% in 2010 to 25% in 2018, as shown in Figure 4.1.

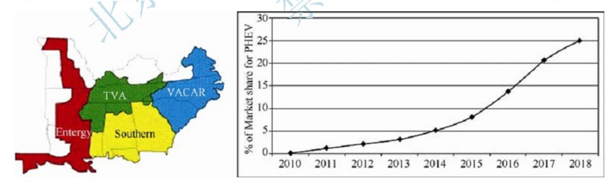



**Figure 4.1 Possible increase in market share for PHEV-20 vehicles in VACAR**

Question: What role do the hybrid and plug-in hybrid electric vehicles play in the future?

## 4.1 Definition

### 4.1.1 Hybrid Vehicles

A hybrid electric vehicle combines a conventional (usually fossil fuel-powered) powertrain

with some form of electric propulsion. Generally, a hybrid vehicle uses two or more distinct types of power, such as internal combustion engine+electric motor, e.g. in diesel-electric trains using diesel engines and electricity from overhead lines, and submarines that use diesels when surfaced and batteries when submerged. Other means to store energy include pressurized fluid, in hydraulic hybrids.

Conventional vehicles use gasoline or diesel to power an internal combustion engine. Hybrids also use an internal combustion engine—and can be fueled like normal cars—but have an electric motor and battery, and can be partially or wholly powered by electricity.

By using both a conventional engine and electric motor, the best hybrids achieve significantly better fuel efficiency than their non-hybrid counterparts. They also pollute less and save drivers money through fuel savings.

As of July 2015, there are over 50 models of hybrid electric cars available in several world markets, with over 10 million hybrid electric vehicles sold worldwide since their inception in 1997. The Toyota Prius (as shown in Figure 4.2) is the world's top selling hybrid electric vehicle, with global sales of 3.6 million units by December 2015.

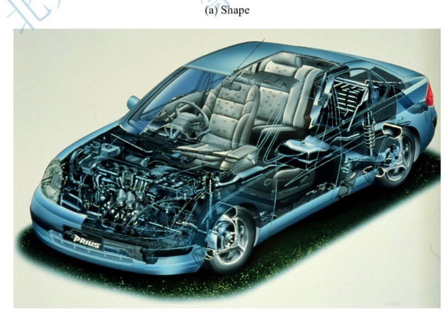




(a) Shape



【参考视频】



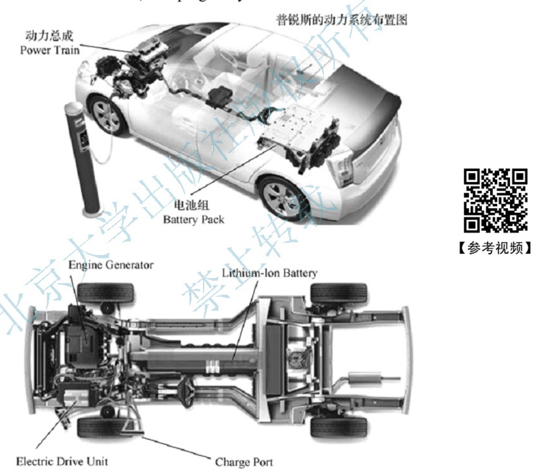

(b) Structure

**Figure 4.2 Toyota Prius**

The most advanced hybrids have larger batteries and can recharge their batteries from an outlet, allowing them to drive extended distances on electricity before switching to gasoline or diesel. Known as "plug-in hybrids", these cars can offer much-improved environmental performance and increased fuel savings by substituting grid electricity for gasoline.

### 4.1.2 Plug-in Hybrid Electric Vehicles

Plug-in hybrid electric vehicles–known as PHEVs–combine a gasoline or diesel engine with an electric motor and a large rechargeable battery, as shown in Figure 4.3. Unlike conventional hybrids, PHEVS can be plugged-in and recharged from an outlet, allowing them to drive extended distances using just electricity. When the battery is emptied, the conventional engine turns on and the vehicle operates as a conventional, non-plug-in hybrid.




【参考视频】



**Figure 4.3 Plug-in hybrid electric vehicles**

Because they can run on electricity from the grid—and because electricity is often a cleaner energy source than gasoline or diesel—plug-in hybrids can produce significantly less global warming pollution than their gas-only counterparts. They don't emit any tailpipe pollution when driving on electricity, and they gain fuel efficiency benefits from having an electric motor and battery. Since they use less gas, they also cost less to fuel: driving a PHEV can save hundreds of dollars a year in gasoline and diesel costs.

### 4.1.3 Differences between Hybrids and Plug-in Hybrids

Conventional hybrids have an electric motor and battery, like plug-ins, but derive all their power from gasoline or diesel and can't be recharged by plugging in. Because of this, non-plug-in hybrids aren't considered electric vehicles (EVs).

Hybrids that can't be recharged from an outlet aren't generally considered to be electric vehicles, as they rely exclusively on gasoline or diesel for energy. Plug-in hybrids are considered electric vehicles, along with battery electric and hydrogen fuel cell vehicles.

## 4.2 Classification

### 4.2.1 Types of Powertrain

#### 4.2.1.1 Series hybrids

A series- or serial-hybrid vehicle is driven by an electric motor, functioning as an electric vehicle while the battery pack energy supply is sufficient, with an engine tuned for running as a generator when the battery pack is insufficient. There is no mechanical connection between the engine and the wheels, and the purpose of the range extender is to charge the battery. Unless there has been a rework of the drivetrain since its first release there is a mechanical linkage in the Chevrolet Volt. Series-hybrids have also been referred to as extended range electric vehicle, range-extended electric vehicle, or electric vehicle-extended range.

In series hybrids, only the electric motor drives the drivetrain, and a smaller internal combustion engine(ICE) works as a generator to power the electric motor or to recharge the batteries, as shown in Figure 4.4. They also usually have a larger battery pack than parallel hybrids, making them more expensive. Once the batteries are low, the small combustion engine can generate power at its optimum settings at all times, making them more efficient in extensive city driving.



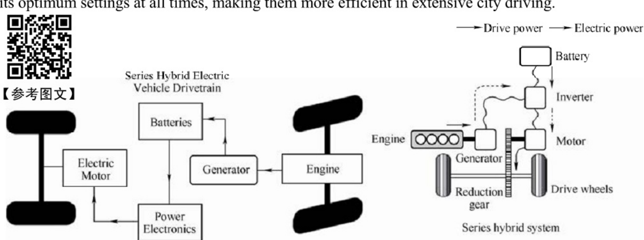



**Figure 4.4 Series Hybrid**

#### 4.2.1.2 Parallel hybrids

In a parallel hybrid vehicle an electric motor and an internal combustion engine are coupled such that they can power the vehicle either individually or together, as shown in Figure 4.5. Most commonly the internal combustion engine, the electric motor and gear box are coupled by automatically controlled clutches. For electric driving the clutch between the internal combustion engine is open while the clutch to the gear box is engaged. While in combustion mode the engine and motor run at the same speed.

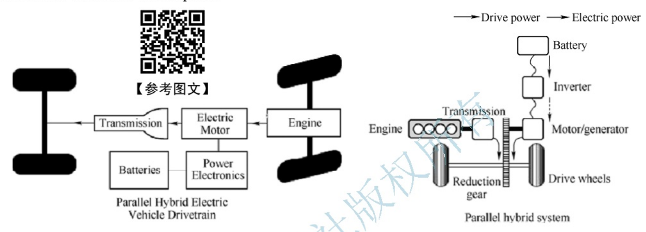



**Figure 4.5 Parallel hybrids**

In parallel hybrids, the ICE and the electric motor are both connected to the mechanical transmission and can simultaneously transmit power to drive the wheels, usually through a conventional transmission, as shown in Figure 4.6. The internal combustion engine of many parallel hybrids can also act as a generator for supplemental recharging. Currently, commercialized parallel hybrids use a full size combustion engine with a single, small (<20kW) electric motor and small battery pack as the electric motor is designed to supplement the main engine, not to be the sole source of motive power from launch.



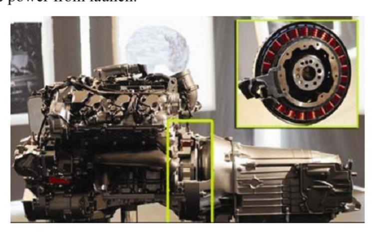





**Figure 4.6 An electric motor fit between engine and transmission in the typical parallel hybrids system**

Parallel hybrids are more efficient than comparable non-hybrid vehicles especially during urban stop-and-go conditions where the electric motor is permitted to contribute, and during

highway operation the series hybrid vehicle is propelled solely by the electric drive system, whereas the Parallel hybrid vehicle is propelled by both the ICE and the electric drive system. A series hybrid will typically require a larger and more powerful battery than a parallel hybrid vehicle in order to meet the performance requirements of the vehicle solely based on battery power.

#### 4.2.1.3 Power-split hybrids

Power-split hybrids have the benefits of a combination of series and parallel characteristics. As a result, they are more efficient overall, because series hybrids tend to be more efficient at lower speeds and parallel tend to be more efficient at high speeds; however, the cost of power-split hybrid is higher than a pure parallel, as shown in Figure 4.7.

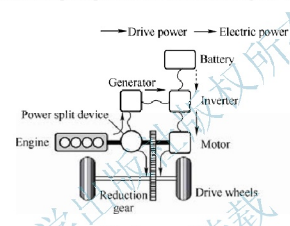



**Figure 4.7 Power-split hybrids**



### 4.2.2 Types by Degree of Hybridization

#### 4.2.2.1 Full hybrids

Full hybrid, sometimes also called a strong hybrid, is a vehicle that can run on just the engine, just the batteries, or a combination of both, as shown in Figure 4.8. These cars can be moved forward on battery power alone. A large, high-capacity battery pack is needed for battery-only operation. These vehicles have a split power path allowing greater flexibility in the drivetrain by interconverting mechanical and electrical power, at some cost in complexity.

#### 4.2.2.2 Mild hybrids

Mild hybrid, is a vehicle that cannot be driven solely on its electric motor, because the electric motor does not have enough power to propel the vehicle on its own, as shown in Figure 4.8. Mild hybrids only include some of the features found in hybrid technology, and usually achieve limited fuel consumption savings, up to 15 percent in urban driving and 8 to 10 percent overall cycle. A mild hybrid is essentially a conventional vehicle with oversize starter motor, allowing the engine to be turned off whenever the car is coasting, braking, or stopped, yet restart quickly and cleanly. The motor is often mounted between the engine and transmission, taking the place of the torque

converter, and is used to supply additional propulsion energy when accelerating. Accessories can continue to run on electrical power while the gasoline engine is off, and as in other hybrid designs, the motor is used for regenerative braking to recapture energy. As compared to full hybrids, mild hybrids have smaller batteries and a smaller, weaker motor/generator, which allows manufacturers to reduce cost and weight.

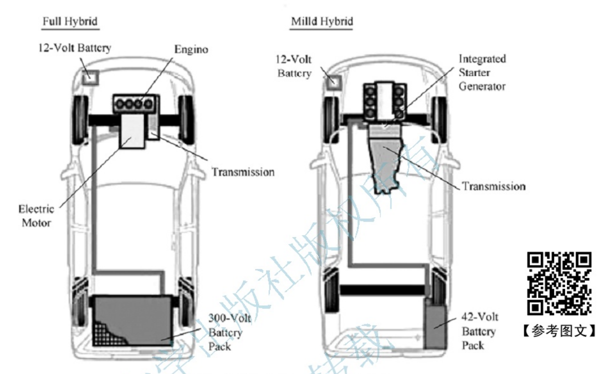



Figure 4.8 Full hybrid and Mild hybrid

### 4.2.2.3 Micro hybrids

Micro-hybrids fit somewhere between the mild hybrid and stop-star systems, as shown in Figure 4.9. There's no need for an electric motor, but a more robust battery is required for the extra stop-start cycles, and to keep useful features like air conditioning running whereas a stop-start- equipped car may not.





【参考图文】

Figure 4.9 Micro-hybrid drive unit

The benefits are potentially great, if not on a car-per-car basis then on a wider scale, since the technology can be applied so widely.

#### 4.2.2.4 Start-stop System

In automobiles, a start-stop system or stop-start system automatically shuts down and restarts the internal combustion engine to reduce the amount of time the engine spends idling, thereby reducing fuel consumption and emissions. This is most advantageous for vehicles which spend significant amounts of time waiting at traffic lights or frequently come to a stop in traffic jams. This feature is present in hybrid electric vehicles, but has also appeared in vehicles which lack a hybrid electric powertrain. For non-electric vehicles (called micro-hybrids), fuel economy gains from this technology are typically in the range of 5 to 10 percent.

### 4.2.3 Difference in HEV Types

Different types of hybrid and electric vehicle concepts exist in the market. Their features are shown in the Table 4.1.

**Table 4.1 Different Types of Hybrid and Electric Vehicle**

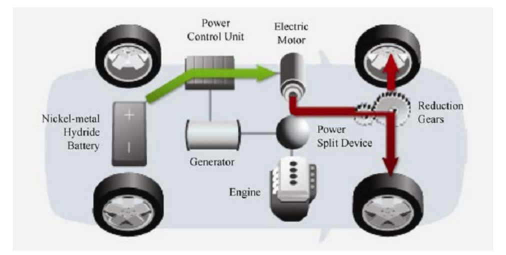
| Feature | Start/ Stop | Micro Hybrid | Mild Hybrid | Full Hybrid (Parallel) | Full Hybrid (Serial) | Full Electric |
|---|---|---|---|---|---|---|
| Start/stop alternator | √ | √ | √ | √ | | |
| Regenerative breaking | | √ | √ | √ | √ | √ |
| Electric torque assist | | | √ | √ | | |
| Electric and combustion drive | | | | √ | | |
| Only electric drive possible | | | | | √ | √ |
| Plug-in Capability | | | | √ | √ | √ |



## 4.3 How HEVs Work

### 4.3.1 Starting Off—Taking advantage of the electric motors' low-speed torque at start-off

When the car starts off, a hybrid vehicle uses only the electric motors, powered by the battery, while the gas/petrol engine remains shut off. A gas/petrol engine cannot produce high torque in the low rpm range, whereas electric motors can, delivering a very responsive and smooth start, as shown in Figure 4.10.





【参考图文】

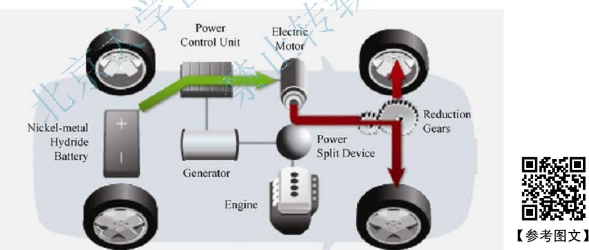
**Figure 4.10 Starting Off**

### 4.3.2 Low-speed Driving—Energy-efficient motor-driven running



A gas/petrol engine is not energy efficient in running a car in the low-speed range. On the other hand, electric motors are energy efficient in running a car in the low-speed range. Therefore, hybrid vehicles use the electric energy stored in its battery to run the car on the electric motors in low-speed range, as shown in Figure 4.11.

If the battery charge level is low, the gas/petrol engine is used to turn the generator to supply power to the electric motors.





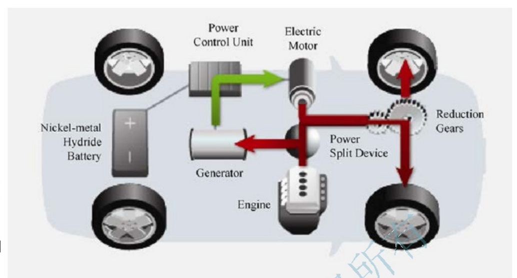
【参考图文】

**Figure 4.11 Low-speed Driving**

### 4.3.3 Cruising—Energy-efficient driving, using the gas/petrol engine as the main power source

Hybrid vehicles use the gas/petrol engine in the speed range in which it operates with good energy efficiency. The power produced by the gas/petrol engine is used to drive the wheels directly, and depending on the driving conditions, part of the power is distributed to the generator. Power produced by the generator is used to feed the electric motors, to supplement the gas/petrol

engine. By making use of the engine/motor dual powertrain, the energy produced by the gas/petrol engine is transferred to the road surface with minimal loss, as shown in Figure 4.12.



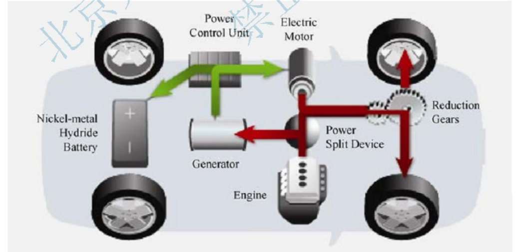

【参考图文】

Figure 4.12　Cruising

If the battery charge level is low, the power output from the gas/petrol engine is increased to increase the amount of electricity generated to recharge the battery.

### 4.3.4　Cruising /Recharging—Recharging the battery with surplus energy

Since hybrid vehicles operate the gas/petrol engine in its high efficiency range, the gas/petrol engine may produce more power than is necessary to drive the car. In this case, the surplus power is converted to electric energy by the generator to be stored in the battery, as shown in Figure 4.13.



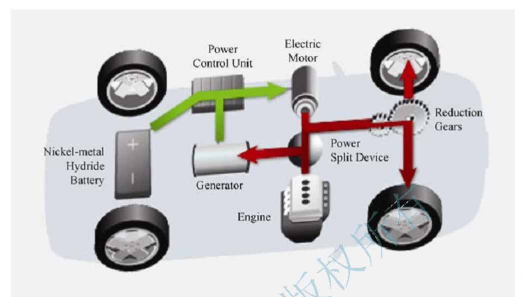

【参考图文】

Figure 4.13　Cruising/Recharging

### 4.3.5　Full Acceleration—Dual power for acceleration one class higher

When strong acceleration is called for (e.g, for climbing a steep slope or overtaking) the power from the battery is supplied to the electric motors to supplement driving power. By

combining the power from the gas/petrol engine and the electric motors, hybrid vehicles deliver power comparable to cars having one class larger engine displacement of one class higher, as shown in Figure 4.14.





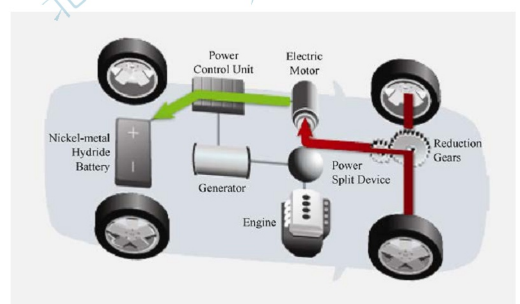
【参考图文】

Figure 4.14 Full Acceleration

### 4.3.6 Deceleration /Regenerating Energy—Storing regenerated energy under deceleration in the battery



Under braking or when the accelerator is lifted, hybrid vehicles use the kinetic energy of the car to let the wheels turn the electric motors, which function as regenerators. Energy that is normally lost as friction heat under deceleration is converted into electrical energy, which is recovered in the battery to be reused later, as shown in Figure 4.15.





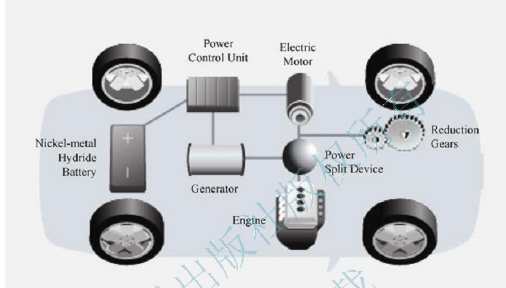
【参考图文】

Figure 4.15 Deceleration/Regenerating Energy

### 4.3.7 At Rest—Shutting down entire powertrain when the car is at rest

The gas/petrol engine, the electric motors and the generator are automatically shut down when the car comes to rest. No energy is wasted by idling.

If the battery charge level is low, the gas/petrol engine is kept running to recharge it. In some cases, the gas/petrol engine may be turned on in conjunction with the air-conditioner switch operation, as shown in Figure 4.16.





【参考图文】

**Figure 4.16 At Rest**



## 4.4 Technologies

### 4.4.1 System Architecture of HEV

The hybrid and electric vehicle system is built of several modules to form the drive train and energy storage system, as shown in Figure 4.17. The battery block (typically a Lithium-ion chemistry in the range of 400V) is managed and monitored by the battery management system (BMS) and charged via an on-board AC/DC converter module, with voltages ranging from 110-V single-phase to 380-V three-phase systems. The DC/AC inverter uses the high voltage of the battery to drive the electric motor, but also is used for regenerative breaking, storing energy back into the battery. To connect the high-voltage battery to the conventional 12-V board net requires a DC/DC converter. The connection of a high-voltage battery to the inverter also requires a reversible DC/DC converter in most cases. The complete HEV system has to meet specific safety requirements that are specifically relevant for managing the high-voltage battery pack, as well as the drive train used for breaking.

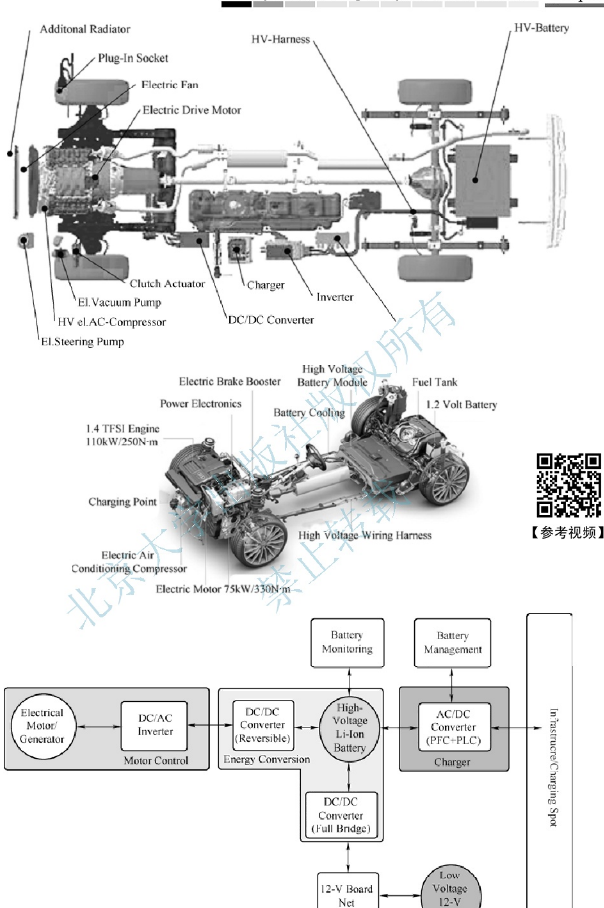


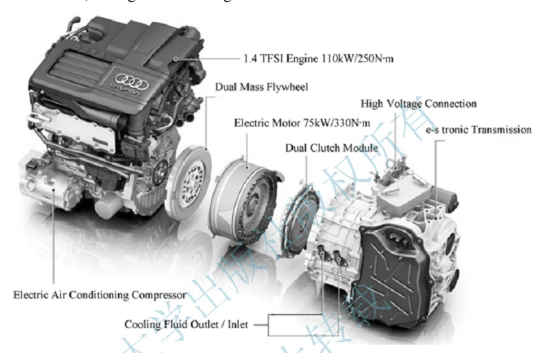





**Figure 4.17 System Architecture of HEV**

### 4.4.2 Electric Machines

Electric motor is fit between engine and transmission in the Figure 4.18. There are two electrical machines, one of which functions as a motor primarily, and the other functions as a generator primarily. One of the primary requirements of these machines is that they should be very efficient, as the electrical portion of the energy must be converted from the engine to the generator, through two inverters, through the motor again and then to the wheels.




【参考图文】

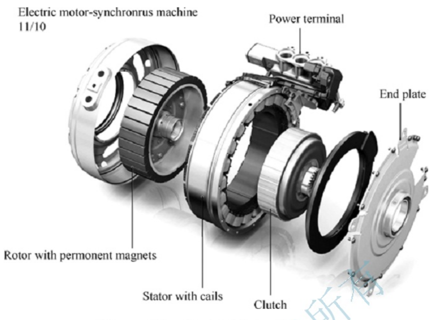
Figure 4.18 Electric motor location



Most of the electric machines used in hybrid vehicles are brushless DC motors (BLDC). Specifically, they are of a type called an interior permanent magnet (IPM) machine (or motor). These machines are wound similarly to the induction motors found in a typical home, but (for high efficiency) use very strong rare earth magnets in the rotor. These magnets contain neodymium, iron and boron, and are therefore called Neodymium magnets. An electric motor structure is shown as the Figure 4.19.

### 4.4.3 Design Considerations

In some cases, manufacturers are producing HEVs that use the added energy provided by the hybrid systems to give vehicles a power boost, rather than significantly improved fuel efficiency compared to their traditional counterparts. The trade-off between added performance and improved fuel efficiency is partly controlled by the software within the hybrid system and partly the result of the engine, battery and motor size. In the future, manufacturers may provide HEV owners with the ability to partially control this balance (fuel efficiency vs. added performance) as they wish, through a user-controlled setting.





【参考图文】

**Figure 4.19 Electric Motor Structure**



# 4.5 Benefit

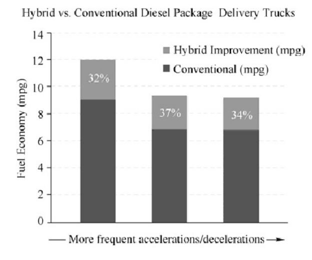
Modern HEVs make use of efficiency-improving technologies such as regenerative brakes, which converts the vehicle's kinetic energy into electric energy to charge the battery, rather than wasting it as heat energy as conventional brakes do. Some varieties of HEVs use their internal combustion engine to generate electricity by spinning an electrical generator (this combination is known as a motor-generator), to either recharge their batteries or to directly power the electric drive motors. Many HEVs reduce idle emissions by shutting down the ICE at idle and restarting it when needed; this is known as a start-stop system. A hybrid-electric produces less emissions from its ICE than a comparably sized gasoline car, since an HEV's gasoline engine is usually smaller than a comparably sized pure gasoline-burning vehicle (natural gas and propane fuels produce lower emissions) and if not used to directly drive the car, can be geared to run at maximum efficiency, further improving fuel economy.

## 4.5.1 High Fuel Economy, Low Operating Cost

Current HEVs reduce petroleum consumption under certain circumstances, compared to otherwise similar conventional vehicles, primarily by using three mechanisms (as shown in Figure 4.20):

- ✧ Reducing wasted energy during idle/low output, generally by turning the ICE off
- ✧ Recapturing waste energy (i.e. regenerative braking)
- ✧ Reducing the size and power of the ICE, and hence inefficiencies from under-utilization,

by using the added power from the electric motor to compensate for the loss in peak power output from the smaller ICE.



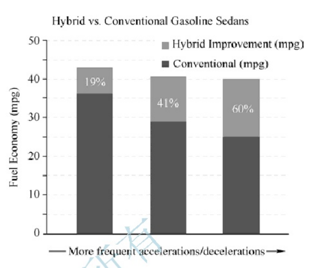




**Figure 4.20 Examples of light- and medium-duty hybrid versus conventional vehicle operation**

Powering a light-duty HEV with electricity costs only 3 to 5 cents per mile. In contrast, fueling a gasoline car that has a fuel economy of 27.5 mpg costs about 14 cents per mile. If 15,000 miles are driven per year, driving the HEV in all-electric mode instead of driving the conventional gasoline car could save $1,300 to $1,600 in annual fuel costs. The fuel economy of medium- and heavy-duty vehicles is highly dependent on the load carried and the duty cycle, but HEVs maintain a strong fuel-cost advantage in this category of vehicles as well.



### 4.5.2 Low Emissions

Hybrid vehicle emissions today are getting close to or even lower than the recommended level set by the EPA (Environmental Protection Agency). The recommended levels they suggest for a typical passenger vehicle should be equated to 5.5 metric tons of carbon dioxide. The three most popular hybrid vehicles, Honda Civic, Honda Insight and Toyota Prius, set the standards even higher by producing 4.1, 3.5, and 3.5 tons showing a major improvement in carbon dioxide emissions. Hybrid vehicles can reduce air emissions of smog-forming pollutants by up to 90% and cut carbon dioxide emissions in half.

### 4.5.3 Noise Reduction

Reduced noise emissions resulting from substantial use of the electric motor at idling and low speeds, leads to roadway noise reduction, in comparison to conventional gasoline or diesel powered engine vehicles, resulting in beneficial noise health effects (although road noise from tires and wind, the loudest noises at highway speeds from the interior of most vehicles, are not affected by the hybrid design alone). Tests have shown that vehicles operating in electric mode can be particularly hard to hear below 20 mph (32 km/h).

## 4.6 Environmental Impact of Hybrid Car Battery

Though hybrid cars consume less fuel than conventional cars, there is still an issue regarding the environmental damage of the hybrid car battery. Today most hybrid car batteries are one of two types: 1) nickel metal hydride, or 2) lithium-ion; both are regarded as more environmentally friendly than lead-based batteries which constitute the bulk of petrol car starter batteries today. There are many types of batteries. Some are far more toxic than others. Lithium-ion is the least toxic of the two mentioned above.

The toxicity levels and environmental impact of nickel metal hydride batteries—the type currently used in hybrids—are much lower than batteries like lead acid or nickel cadmium according to one source. Another source claims nickel metal hydride batteries are much more toxic than lead batteries, also that recycling them and disposing of them safely is difficult. In general various soluble and insoluble nickel compounds, such as nickel chloride and nickel oxide, have known carcinogenic effects in chick embryos and rats. The main nickel compound in NiMH batteries is nickel oxyhydroxide (NiOOH), which is used as the positive electrode.

The lithium-ion battery has attracted attention due to its potential for use in hybrid electric vehicles. Hitachi is a leader in its development. In addition to its smaller size and lighter weight, lithium-ion batteries deliver performance that helps to protect the environment with features such as improved charge efficiency without memory effect. The lithium-ion batteries are appealing because they have the highest energy density of any rechargeable batteries and can produce a voltage more than three times that of nickel–metal hydride battery cell while simultaneously storing large quantities of electricity as well. The batteries also produce higher output (boosting vehicle power), higher efficiency (avoiding wasteful use of electricity), and provides excellent durability, compared with the life of the battery being roughly equivalent to the life of the vehicle. Additionally, use of lithium-ion batteries reduces the overall weight of the vehicle and also achieves improved fuel economy of 30% better than petro-powered vehicles with a consequent reduction in $CO_2$ emissions helping to prevent global warming.



## 4.7 Driving and Maintaining HEV

HEVs are at least as easy to operate and maintain as conventional vehicles, but some special considerations apply.

### 4.7.1 Vehicle Maintenance

Because HEVs have ICEs, maintenance requirements for this system are similar to those in

conventional vehicles. However, the HEV electrical system (battery, motor, and associated electronics) likely will require minimal scheduled maintenance. Because of regenerative braking, brake systems on HEVs typically last longer than on conventional vehicles. In general, HEVs require less maintenance than conventional vehicles do, because there are usually fewer fluids to change and far fewer moving parts.

### 4.7.2 Battery Life

Like the ICEs in conventional vehicles, the advanced batteries in HEVs are designed for extended life but will wear out eventually. Currently, manufacturers are offering eight-year/100,000-mile warranties for the batteries. HEV dealerships will have specific information about battery life and warranties. Although manufacturers have not published pricing for replacement batteries, if the batteries need to be replaced outside the warranty, it is expected to be a significant expense. However, battery prices should decline as the benefits of technological improvements and economies of scale are realized.

### 4.7.3 Safety

HEVs must undergo the same rigorous safety testing and meet the same safety standards required for conventional vehicles sold in the United States. In addition, a PEV-specific standard sets requirements for limiting chemical spillage, securing batteries during a crash, and isolating the chassis from the high-voltage system to prevent electric shock. HEV manufacturers have designed their vehicles with safety features that deactivate the high-voltage electric system in the event of a collision. EVs tend to have a lower center of gravity than conventional vehicles, making them less likely to roll over and often improving ride quality.

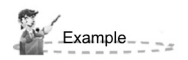





1. What is the difference between hybrid vehicles and plug-in hybrid electric vehicles?
2. What are the advantages of HEVs?
3. What is the environmental impact of hybrid car battery?
4. What should you pay attention to when driving and maintaining an HEV?
5. What are the types of HEVs?

# Chapter 5

# Alternative Fuel Vehicle




Within the transportation industry, including trucks and delivery vans, transit vehicles account for less than 2% of the total fuel consumed. Diesel is the most commonly used transit fuel. Use of other fuels, known as alternative fuels, is limited but growing. Table 5.1, based on a survey of 300 transit agencies by the American Public Transportation Association, shows the dominance of petroleum diesel fuel use in transit vehicles of various types.

**Table 5.1 Survey of U.S. Transit Vehicles by Power Source and Type of Vehicle**

| Power Source | Bus | Commuter Rail Car | Commuter Rail Locomotive | Heavy Rail | Light Rail | Paratransit | Trolley Bus | Other | Subotals | Percent |
|---|---|---|---|---|---|---|---|---|---|---|
| Diesel | 46,266 | 18 | 639 | | 24 | 7,714 | | 286 | 54,947 | 57.9 |
| Ultra-Low Sulfur Diesel | 618 | | | | | 207 | | | 825 | 0.3 |
| Gasoline | 336 | | | | | 3,498 | | 3,969 | 7,803 | 8.2 |
| Liquefied Natural Gas | 1,092 | | | | | 38 | | | 1,130 | 1.2 |
| Propane | 310 | | | | | 161 | | | 471 | 0.5 |
| Compressed Natural Gas | 7,488 | | | | | 311 | | 30 | 7,829 | 8.3 |
| CNG Blends | 169 | | | | | 2 | | | 171 | 0.2 |
| Electric & Diesel | 750 | | | | | | 26 | 28 | 804 | 0.8 |
| Electric & Other | 211 | | | | | | | 15 | 226 | 0.3 |
| Electric Third Rail or Catenary | | 3,008 | 79 | 11,151 | 2,046 | | 686 | 144 | 17,114 | 18.0 |

Continued

| Power Source | Bus | Commuter Rail Car | Commuter Rail Loco-motive | Heavy Rail | Light Rail | Paratransit | Trolley Bus | Other | Subotals | Percent |
|---|---|---|---|---|---|---|---|---|---|---|
| Other | 376 | | | | | 39 | | | 415 | 0.4 |
| Unpowered | | 3,044 | | 3 | | | | 49 | 3,096 | 3.3 |
| Totals | 57,616 | 6,070 | 718 | 11,154 | 2,070 | 11,970 | 712 | 4,521 | 94,831 | 100.0 |

Question: What are the main alternative fuels?

## 5.1 Alternative Energy

Alternative energy is any energy source that is an alternative to fossil fuel. These alternatives are intended to address concerns about such fossil fuels. It causes less pollution too.

The nature of what constitutes an alternative energy source has changed considerably over time, as have controversies regarding energy use. Today, because of the variety of energy choices and differing goals of their advocates, defining some energy types as “alternative” is highly controversial.

In a general sense, alternative energy as it is currently conceived, is that which is produced or recovered without the undesirable consequences inherent in fossil fuel use, particularly high carbon dioxide emissions (greenhouse gas), an important factor in global warming.

The following fuels are considered alternative fuels:

- Alternative diesel (including biodiesel, Fischer-Tropsch and diesel blends);
- Methanol, ethanol, and other alcohols;
- Liquefied petroleum gas (propane);
- Blends of 85 percent or more of alcohol with gasoline;
- Coal-derived liquid fuels;
- Fuels (other than alcohol) derived from biological materials;
- Natural gas and liquid fuels domestically produced from natural gas.

### Alternative Diesel

Alternative Diesel is the name for a variety of non-petroleum fuels and petroleum diesel blends that can be used in diesel engines. Some examples include biodiesel, Fischer-Tropsch diesel, and ethanol/diesel blends. Each promises emissions benefits compared to neat petroleum diesel.

- ✧ Biodiesel is a fuel derived from vegetable oils or animal fats. It is typically blended with petroleum diesel at a concentration of 20 percent biodiesel (known as B20) as this blend represents a good balance of emission benefits, cost and risk of field problems. B20 is commonly used in diesel engines with no modifications.
- ✧ Fischer-Tropsch diesel is a synthetic diesel fuel made from coal, natural gas, or biomass feedstock via the Fischer-Tropsch process. The fuel has the same properties regardless of

the feedstock. No engine modifications are required to use Fischer-Tropsch diesel, whether alone or blended with petroleum diesel.

- Diesel/Alcohol blends, also called diesohol or oxygenated diesel, are petroleum diesel blends containing up to 15 percent ethanol or methanol.

### Methanol, ethanol, and other alcohols

- Ethanol is also known as ethyl alcohol or grain alcohol. It is primarily fermented from grains, such as corn or other agricultural products. The form of ethanol typically used in transportation is known as E85 and contains 15 percent gasoline. All flex-fuel light-duty vehicles are designed to use E85. During the 1990s, the Los Angeles County Metropolitan Transportation Authority operated an ethanol bus fleet.
- Methanol, also called methyl alcohol, is a clear, odorless liquid typically made from natural gas, though it can also be made from coal, wood or various grains. In heavy-duty vehicles, methanol is typically used unblended, though it is also sold as M85, which contains 15 percent gasoline. Methanol powered transit vehicles were used in significant numbers in the 1990s, when the Los Angeles County Metropolitan Transportation Authority operated more than 300 of them.

### Liquefied petroleum gas (propane)

Liquefied petroleum gas, also called propane or LPG, is a by-product of petroleum refining and natural gas processing. In the U.S., most propane comes from natural gas processing plants. Propane is gaseous at room temperature and atmospheric pressure but liquefies easily at moderate pressure. Natural gas comes in two forms: compressed (CNG) and liquefied (LNG). If the gas is compressed, it typically comes through a utility pipeline. If the gas is liquefied, it is typically delivered by tanker truck.



## 5.2 Alternative Fuel Vehicle

An alternative fuel vehicle is a vehicle that runs on a fuel other than traditional petroleum fuels (petrol or diesel fuel); and also refers to any technology of powering an engine that does not involve solely petroleum (e.g. electric car, hybrid electric vehicles, solar powered). Because of a combination of factors, such as environmental concerns, high oil prices and the potential for peak oil, development of cleaner alternative fuels and advanced power systems for vehicles has become a high priority for many governments and vehicle manufacturers around the world.

Hybrid electric vehicles such as the Toyota Prius are not actually alternative fuel vehicles, but through advanced technologies in the electric battery and motor/generator, they make a more efficient use of petroleum fuel. Other research and development efforts in alternative forms of

power focus on developing all-electric and fuel cell vehicles, and even the stored energy of compressed air.

As of 2011 there were more than one billion vehicles in use in the world, compared with over 100 million alternative fuel and advanced technology vehicles that had been sold or converted worldwide as of September 2015, and made up mainly of:

- ✧ About 48 million automobiles, motorcycles and light duty trucks manufactured and sold worldwide by mid 2015;
- ✧ 22.7 million natural gas vehicles as of August 2015;
- ✧ 24.9 million LPG powered vehicles by December 2013;
- ✧ Over 10 million hybrid electric vehicles have been sold worldwide as of July 2015;
- ✧ 5.7 million neat-ethanol only light-vehicles built in Brazil;
- ✧ Over one million highway legal plug-in electric passenger cars and light utility vehicles have been sold worldwide by mid-September 2015.

In Brazil, some filling station provide four alternative fuels, as shown in Figure 5.1.


【参考图文】



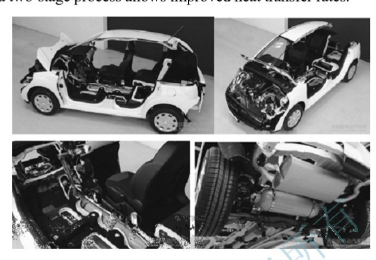

**Figure 5.1 A Brazilian filling station with four alternative fuels for sale: biodiesel (B3), gasohol (E25), neat ethanol (E100), and compressed natural gas (CNG)**

An environmental analysis extends beyond just the operating efficiency and emissions. A life-cycle assessment of a vehicle involves production and post-use considerations. A cradle-to-cradle design is more important than a focus on a single factor such as the type of fuel.

### 5.2.1 Air Engine

The air engine is an emission-free piston engine that uses compressed air as a source of energy. The first compressed air car (as shown in Figure 5.2) was invented by a French engineer named Guy Nègre. The expansion of compressed air may be used to drive the pistons in a modified piston engine. Efficiency of operation is gained through the use of environmental heat at normal temperature to warm the otherwise cold expanded air from the storage tank. This non-adiabatic expansion has the potential to greatly increase the efficiency of the machine. The only exhaust is cold air (−15 °C), which could also be used to air condition the car. The source for air is

a pressurized carbon-fiber tank. Air is delivered to the engine via a rather conventional injection system. Unique crank design within the engine increases the time during which the air charge is warmed from ambient sources and a two-stage process allows improved heat transfer rates.





【参考图文】

**Figure 5.2 Air engine vehicle**



### 5.2.2 Dimethyl Ether Fuel

Dimethyl ether (DME) is a promising fuel in diesel engines, petrol engines (30% DME / 70% LPG), and gas turbines owing to its high cetane number, which is 55, compared with diesel's, which is 40–53. Only moderate modification are needed to convert a diesel engine to burn DME. The simplicity of this short carbon chain compound leads during combustion to very low emissions of particulate matter, $NO_x$, CO. For these reasons as well as being sulfur-free, DME meets even the most stringent emission regulations in Europe (EURO5), U.S. (U.S. 2010), and Japan (2009 Japan). Mobil is using DME in their methanol to gasoline process.

DME is being developed as a synthetic second generation biofuel (BioDME), which can be manufactured from lignocellulosic biomass. Currently the EU is considering BioDME in its potential biofuel mix in 2030; the Volvo Group is the coordinator for the European Community Seventh Framework Programme project BioDME where Chemrec's BioDME pilot plant based on black liquor gasification is nearing completion in Piteå, Sweden, as shown in Figure 5.3.



**Figure 5.3 Installation of BioDME synthesis towers at Chemrec's pilot facility**

### 5.2.3 Ammonia Fuelled Vehicles

Ammonia is produced by combining gaseous hydrogen with nitrogen from the air. Large-scale ammonia production uses natural gas for the source of hydrogen. Ammonia was used during World War II to power buses in Belgium, and in engine and solar energy applications prior to 1900. Liquid ammonia also fuelled the Reaction Motors XLR99 rocket engine, that powered the X-15 hypersonic research aircraft,as shown in Figure 5.4. Although not as powerful as other fuels, it left no soot in the reusable rocket engine and its density approximately matches the density of the oxidizer, liquid oxygen, which simplified the aircraft's design.






**Figure 5.4 The X-15 aircraft used ammonia as one component fuel of its rocket engine**

Ammonia has been proposed as a practical alternative to fossil fuel for internal combustion engines. The calorific value of ammonia is 22.5 MJ/kg (9690 BTU/lb), which is about half that of diesel. In a normal engine, in which the water vapour is not condensed, the calorific value of ammonia will be about 21% less than this figure. It can be used in existing engines with only minor modifications to carburetors/injectors.

If produced from coal, the $CO_2$ can be readily sequestered (the combustion products are nitrogen and water).

Ammonia engines or ammonia motors, using ammonia as a working fluid, have been proposed and occasionally used. The principle is similar to that used in a fireless locomotive, but with ammonia as the working fluid, instead of steam or compressed air. Ammonia engines were used experimentally in the 19th century by Goldsworthy Gurney in the UK and in streetcars in New Orleans. In 1981 a Canadian company converted a 1981 Chevrolet Impala to operate using ammonia as fuel.

Ammonia and Green$NH_3$ is being used with success by developers in Canada, since it can run in spark ignited or diesel engines with minor modifications, also the only green fuel to power jet engines, and despite its toxicity is reckoned to be no more dangerous than petrol or LPG. It can be made from renewable electricity, and having half the density of petrol or diesel can be readily

carried in sufficient quantities in vehicles. On complete combustion it has no emissions other than nitrogen and water vapour. The combustion chemical formula is $4NH_3 + 3O_2 \rightarrow 2N_2 + 6H_2O$, 75% water is the result.

### 5.2.4 Bioalcohol and Ethanol

The first commercial vehicle that used ethanol as a fuel was the Ford Model T, produced from 1908 through 1927. It was fitted with a carburetor with adjustable jetting, allowing use of gasoline or ethanol, or a combination of both. Other car manufactures also provided engines for ethanol fuel use. In the United States, alcohol fuel was produced in corn-alcohol stills until Prohibition criminalized the production of alcohol in 1919. The use of alcohol as a fuel for internal combustion engines, either alone or in combination with other fuels, lapsed until the oil price shocks of the 1970s. Furthermore, additional attention was gained because of its possible environmental and long-term economical advantages over fossil fuel.

Both ethanol and methanol have been used as an automotive fuel. While both can be obtained from petroleum or natural gas, ethanol has attracted more attention because it is considered a renewable resource, easily obtained from sugar or starch in crops and other agricultural produce such as grain, sugarcane, sugar beets or even lactose. Since ethanol occurs in nature whenever yeast happens to find a sugar solution such as overripe fruit, most organisms have evolved some tolerance to ethanol, whereas methanol is toxic. Other experiments involve butanol, which can also be produced by fermentation of plants. Support for ethanol comes from the fact that it is a biomass fuel, which addresses climate change and greenhouse gas emissions, though these benefits are now highly debated, including the heated 2008 food vs fuel debate.

Most modern cars are designed to run on gasoline are capable of running with a blend from 10% up to 15% ethanol mixed into gasoline (E10-E15). With a small amount of redesign, gasoline-powered vehicles can run on ethanol concentrations as high as 85% (E85), the maximum set in the United States and Europe due to cold weather during the winter, or up to 100% (E100) in Brazil, with a warmer climate. Ethanol has close to 34% less energy per volume than gasoline, consequently fuel economy ratings with ethanol blends are significantly lower than with pure gasoline, but this lower energy content does not translate directly into a 34% reduction in mileage, because there are many other variables that affect the performance of a particular fuel in a particular engine, and also because ethanol has a higher octane rating which is beneficial to high compression ratio engines.

For this reason, for pure or high ethanol blends to be attractive for users, its price must be lower than gasoline to offset the lower fuel economy. As a rule of thumb, Brazilian consumers are frequently advised by the local media to use more alcohol than gasoline in their mix only when ethanol prices are 30% lower or more than gasoline, as ethanol price fluctuates heavily depending on the results and seasonal harvests of sugar cane and by region. In the US, and based on EPA tests for all 2006 E85 models, the average fuel economy for E85 vehicles was found 25.56%




Figure 5.5 E85 fuel sold at a regular gasoline station in Washington, D.C.

【参考图文】

lower than unleaded gasoline, as shown in Figure 5.5. The EPA-rated mileage of current American flex-fuel vehicles could be considered when making price comparisons, though E85 has octane rating of about 104 and could be used as a substitute for premium gasoline. Regional retail E85 prices vary widely across the US, with more favorable prices in the Midwest region, where most corn is grown and ethanol produced. In August 2008 the US average spread between the price of E85 and gasoline was 16.9%, while in Indiana was 35%, 30% in Minnesota and Wisconsin, 19% in Maryland, 12 to 15% in California, and just 3% in Utah. Depending of the vehicle capabilities, the break even price of E85 usually has to be between 25 to 30% lower than gasoline.

### 5.2.5 Biodiesel

The main benefit of diesel combustion engines is that they have a 44% fuel burn efficiency; compared with just 25%–30% in the best gasoline engines. In addition diesel fuel has slightly higher energy density by volume than gasoline. This makes diesel engines capable of achieving much better fuel economy than gasoline vehicles, as shown in Figure 5.6.






Figure 5.6 Biodiesel (B20) pump in the U.S.


【参考图文】

Biodiesel (Fatty acid methyl ester), is commercially available in most oilseed-producing states in the United States. As of 2005, it is somewhat more expensive than fossil diesel, though it is still commonly produced in relatively small quantities (in comparison to petroleum products and ethanol). Many farmers who raise oilseeds use a biodiesel blend in tractors and equipment as a matter of policy, to foster production of biodiesel and raise public awareness. It is sometimes easier to find biodiesel in rural areas than in cities. Biodiesel has lower energy density than fossil diesel fuel, so biodiesel vehicles are not quite able to keep up with the fuel economy of a fossil fuelled diesel vehicle, if the diesel injection system is not reset for the new fuel. If the injection timing is changed to take account of the higher cetane value of biodiesel, the difference in economy is negligible. Because biodiesel contains more oxygen than diesel or vegetable oil fuel, it produces the lowest emissions from diesel engines, and is lower in most emissions than gasoline engines. Biodiesel has a higher lubricity than mineral diesel and is an additive in European pump diesel for lubricity and emissions reduction. The bus runs on soybean biodiesel is shown in Figrue 5.7.






【参考图文】

**Figure 5.7 Bus running on soybean biodiesel**

Some diesel-powered cars can run with minor modifications on 100% pure vegetable oils. Vegetable oils tend to thicken (or solidify if it is waste cooking oil), in cold weather conditions so vehicle modifications (a two-tank system with diesel start/stop tank), are essential in order to heat the fuel prior to use under most circumstances. Heating to the temperature of engine coolant reduces fuel viscosity, to the range cited by injection system manufacturers, for systems prior to “common rail” or “unit injection”systems. Waste vegetable oil, especially if it has been used for a long time, may become hydrogenated and have increased acidity. This can cause the thickening of fuel, gumming in the engine and acid damage of the fuel system. Biodiesel does not have this problem, because it is chemically processed to be PH neutral and lower viscosity. Modern low emission diesels (most often Euro -3 and -4 compliant), typical of the current production in the

European industry, would require extensive modification of injector system, pumps and seals etc. due to the higher operating pressures, that are designed thinner (heated) mineral diesel than ever before, for atomisation, if they were to use pure vegetable oil as fuel. Vegetable oil fuel is not suitable for these vehicles as they are currently produced. This reduces the market as increasing numbers of new vehicles are not able to use it. However, the German Elsbett company has successfully produced single tank vegetable oil fuel systems for several decades, and has worked with Volkswagen on their TDI engines. This shows that it is technologically possible to use vegetable oil as a fuel in high efficiency/low emission diesel engines.

### 5.2.6 Compressed Natural Gas

High-pressure compressed natural gas, mainly composed of methane, that is used to fuel normal combustion engines instead of gasoline. Combustion of methane produces the least amount of $CO_2$ of all fossil fuels. Gasoline cars can be retrofitted to CNG and become bi-fuel natural gas vehicles (NGVs) as the gasoline tank is kept. The driver can switch between CNG and gasoline during operation. Natural gas vehicles (NGVs) are popular in regions or countries where natural gas is abundant. Widespread use began in the Po River Valley of Italy, and later became very popular in New Zealand by the eighties, though its use has declined.

CNG vehicles are common in South America, as shown in Figure 5.8 where these vehicles are mainly used as taxicabs in main cities of Argentina and Brazil. Normally, standard gasoline vehicles are retrofitted in specialized shops, which involve installing the gas cylinder in the trunk and the CNG injection system and electronics. The Brazilian GNV fleet is concentrated in the cities of Rio de Janeiro and São Paulo, as shown in Figure 5.9. Pike Research reports that almost 90% of NGVs in Latin America have bi-fuel engines, allowing these vehicles to run on either gasoline or CNG.


【参考图文】




**Figure 5.8 Buses powered with CNG are common in the United States**




【参考图文】

**Figure 5.9 The Brazilian Fiat Siena Tetrafuel 1.4, the first multifuel car that runs as a flexible-fuel on pure gasoline, or E25, or E100; or runs as a bi-fuel with natural gas (CNG)**



### 5.2.7 Liquefied Propane Gas(LPG)

Propane is a cleaner burning, high performance fuel derived from multiple sources. It is known by many names including propane, LPG (liquified propane gas), or liquefied petroleum gas. It is a low pressure liquefied gas mixture composed mainly of propane and butane which burns in conventional gasoline combustion engines with less $CO_2$ than gasoline. Gasoline cars can be retrofitted to LPG, also known as autogas and become bi-fuel vehicles as the gasoline tank stays. You can switch between LPG and gasoline during operation. It is estimated that 10 million vehicles are running worldwide. A propane-fueled school bus is shown in U.S.





【参考图文】

**Figure 5.10 A propane-fueled school bus in the United States**

### 5.2.8 Flexible Fuel

A flexible-fuel(flex-fuel) vehicle (FFV) or dual-fuel vehicle is an alternative fuel automobile or light duty truck with a multifuel engine that can use more than one fuel, usually mixed in the same tank, and the blend is burned in the combustion chamber together. These vehicles are colloquially called flex-fuel, or flexifuel in Europe, or just flex in Brazil. FFVs are distinguished from bi-fuel vehicles, where two fuels are stored in separate tanks. The most common commercially available FFV in the world market is the ethanol flexible-fuel vehicle, with the major markets concentrated in the United States, Brazil, Sweden, and some other European countries. In addition to flex-fuel vehicles running with ethanol, in the US and Europe there were successful test programs with methanol flex-fuel vehicles, known as M85 FFVs, and more recently there have been also successful tests using p-series fuels with E85 flex fuel vehicles, but as of June 2008, this fuel is not yet available to the general public.

Ethanol flexible-fuel vehicles have standard gasoline engines that are capable of running with ethanol and gasoline mixed in the same tank. These mixtures have “E” numbers which describe the percentage of ethanol in the mixture, for example, E85 is 85% ethanol and 15% gasoline. (See common ethanol fuel mixtures for more information.) Though technology exists to allow ethanol FFVs to run on any mixture up to E100, in the U.S. and Europe, flex-fuel vehicles are optimized to run on E85. This limit is set to avoid cold starting problems during very cold weather. The alcohol content might be reduced during the winter, to E70 in the U.S. or to E75 in Sweden. Brazil, with a warmer climate, developed vehicles that can run on any mix up to E100, though E20–E25 is the mandatory minimum blend, and no pure gasoline is sold in the country.



In the United States, E85 FFVs are equipped with sensor that automatically detect the fuel mixture, signaling the ECU to tune spark timing and fuel injection so that fuel will burn cleanly in the vehicle’s internal combustion engine. Originally, the sensors were mounted in the fuel line and exhaust system; more recent models do away with the fuel line sensor. Another feature of older flex-fuel cars is a small separate gasoline storage tank that was used for starting the car on cold days, when the ethanol mixture made ignition more difficult.

Modern Brazilian flex-fuel technology enables FFVs to run an any blend between E20-E25 gasohol and E100 ethanol fuel, using a lambda probe to measure the quality of combustion, as shown in Figure 5.11. which informs the engine control unit as to the exact composition of the gasoline-alcohol mixture. This technology allows the controller to regulate the amount of fuel injected and spark time, as fuel flow needs to be decreased to avoid detonation due to the high compression ratio (around 12:1) used by flex-fuel engines.



【参考图文】

**Figure 5.11 Six typical Brazilian full flex-fuel models from several carmakers, popularly known as "flex" cars, that run on any blend of ethanol and gasoline(actually between E20-E25 to E100).**

## 5.3 Emissions from Alternative Fuels

Reduction of tailpipe emissions is the single greatest environmental benefit of alternative fuels use in public transportation vehicles. Diesel exhaust is particularly hazardous to breathe, even at emission levels equivalent to alternative fuels. Alternative fuel engines typically offer lower emission rates for PM, $NO_x$, and HC than diesels in all kinds of transit vehicles.

New emission regulations applied to all bus engines will require major reductions in emission

rates, especially for diesels. The new regulations could equalize the diesel baseline emissions of regulated pollutants with those of alternative fuels like ethanol, methanol, propane, CNG, and LNG. Alternative fuels that can be used in diesel engines, such as Fischer-Tropsch diesel and certain alternative diesel blends, will continue to offer emissions rates lower than the diesel baseline.

While using alternative fuels to reduce emissions from transit vehicles improves local air quality, controlling the sizes and types of vehicles used in transit operations could make an even greater difference. Managing a fleet to minimize cumulative emissions throughout the day, for example, by using smaller buses in low-density service areas and off-peak periods, could reduce emissions and energy use per vehicle-mile of operation.

Compared with other fuels' emissions, diesel exhaust is particularly hazardous to breathe, even at equivalent emission rates. Diesel also generates larger amounts of life-cycle greenhouse gas emissions than nearly every other fuel reviewed. Finally, spills and leaks of most alternative fuels, unlike those of diesel or diesel alternatives, vent or evaporate without long-term damage to soil or groundwater.

Below is a summary of heavy-duty bus emissions, focusing on PM, $NO_x$, and HC emissions (heavy-duty vehicles are not a major source of CO). Each fuel has its own emissions profile, which is described in detail. Most alternative fuels have lower emissions than today's diesels but must achieve significant reductions to meet emissions standards. Other alternative fuels offer zero or near-zero emissions performance today. The emissions data presented in Table 5.2 were used to estimate average PM, $NO_x$, and NMHC emission rates for each alternative fuel. In the table, emission rates that meet heavy-duty diesel emissions standards are in boldface. Each alternative fuel reviewed in this study offers some combination of emissions benefits compared to emission standards for diesel technology.



**Table 5.2 Comparison of bus engine emissions with emissions standards. (Levels meeting or exceeding standards shown in italics).**

| Fuel | PM(g/bhp-hr) | $NO_x$(g/bhp-hr) | NMHC(g/bhp-hr) |
|---|---|---|---|
| 2007-2010 EPA Standards | 0.01 | 0.2 | 0.14 |
| Current diesel (baseline) | 0.026 | 2.36 | 0.11 |
| $O_2$ Diesel™ | 0.021 | 2.32 | 0.083 |
| B20 | 0.023 | 2.41 | 0.087 |
| B100 | 0.014 | 2.60 | 0.036 |
| Fischer-Tropsch | 0.023 | 2.15 | 0.086 |
| Ethanol | 0.026 | 1.77 | 0.45 |
| Methanol | 0.026 | 1.18 | 0.11 |
| Propane | 0.01 | 1.18 | 0.5 |
| CNG | 0.006 | 1.24 | 0.13 |
| LNG | 0.006 | 1.24 | 0.13 |
| Hydrogen ICE | Trace | Low | Trace |
| Hydrogen Fuel Cell | 0 | 0 | 0 |
| Electricity | 0 | 0 | 0 |

Although this section focuses on emissions that may cause air pollution, it is important to point out that alternative fuels are less likely to have the same environmental impact on soil or water as diesel fuel in the event of a spill or leak of fuel, such as could occur in the area surrounding a transit fueling or maintenance facility. Spills of diesel fuel and Fischer-Tropsch diesel can contaminate soil and groundwater because they are not biodegradable. In contrast, most liquid alternative fuels, including methanol, ethanol, and biodiesel, are biodegradable over a short period of time (several months). Liquefied fuels like propane, natural gas, and hydrogen, vaporize quickly when released but present explosive hazards unless promptly vented.

The diesel bus engines can operate on certain alternative diesel and alternative diesel blends. Four such fuels—oxygenated diesel, B20, B100, and Fischer-Tropsch diesel—can be used in existing diesel engines with few or no modifications.

Fuels such as CNG and LNG nearly meet diesel bus emission standards for all three pollutants (CO was not considered). Engines burning these fuels use less sophisticated emission controls than today's cleanest diesel engines. Methanol and propane meet the standards for two out of three pollutants. Clean diesel and alternative diesel meet only the NMHC standards, so more effective emission controls are required. Hydrogen and electricity offer zero or near-zero tailpipe emissions.

With the new EPA regulations, all heavy-duty bus engines must soon meet the same standards. These standards are so stringent that they require improved emission control strategies for every diesel and alternative fuel engine except for those using hydrogen and electricity. Engine manufacturers have announced that they will continue to offer dedicated alternative fuel bus engines, like CNG, LNG, and propane, that offer lower emissions of PM and $NO_x$ compared to diesel engines.

Manufacturers have also indicated that engines designed for alternative fuels will offer further $NO_x$ emissions reductions, so they will "beat" the $NO_x$ standards by an unspecified amount. The exact emissions benefits of alternative fuels and later diesels will remain uncertain until the newest engines are certified. Alternative fuels might even offer reduced emission rates of PM and $NO_x$ compared to diesels, just as they do today. For instance, CNG test engines equipped with exhaust gas recirculation have demonstrated emissions below the current standards.

The mix of diesel and alternative fuel bus engines to be offered by major heavy-duty engine manufacturers is not known precisely. Key engine manufacturers have indicated that they plan to produce diesel and natural gas bus engines. Also, it is very likely that electric drive motors will be available in production quantities. However, it is unclear whether other dedicated alternative fuel bus engines (such as propane, ethanol, and methanol) will be mass produced.

Alternative diesels are compatible with the new emission control devices and later diesel engines. Thus, alternative fuels like Fischer-Tropsch, biodiesel, and diesel blends, because of their cleaner burning properties, will likely continue to offer reduced emissions compared to petroleum diesel. The exact emissions benefits will not be known until the new engines are tested with these

fuels. Still, emission reductions on a percentage basis compared to the diesel baseline are not expected to change significantly even as the diesel baseline becomes much cleaner.

To meet the $NO_x$ and PM standards, new diesel engines will be equipped with new emission controls enabled by the recent availability of ultra-low sulfur diesel (ULSD) fuel. To control $NO_x$ emissions, manufacturers will use a number of design features that include high-flow, cooled EGR plus combustion, fuel injection system, and control system upgrades. To meet PM standards, manufacturers will equip all bus engines with diesel particulate filters. To meet $NO_x$ standards, a number of aftertreatment devices are in development. These include $NO_x$ adsorber catalysts and selective catalytic reduction.

Emission reduction technologies can be applied to many alternative fuels to achieve emission reductions. However, the effect of the standards is to encourage manufacturers to produce engines with the same emissions regardless of fuel type. Today's CNG and propane buses are equipped with less effective emission controls because they can meet the standards without them; this pattern is likely to continue as there is little incentive for manufacturers to outperform the emissions standards.

Some buses running on alternative fuels with relatively simpler emission controls can meet the standards today. Alternative fuel buses will continue to appeal to a number of transit agencies due to their relatively simpler exhaust treatment and potential for even greater emissions reductions.



## 5.4 Others

### 5.4.1 Diesel Emulsion

The addition of water into the combustion chamber lowers the peak combustion temperatures by using the heat in the chamber to vaporise the water in the emulsion. 40%–50% reductions of both $NO_x$ and PM have been reported with little or no fuel consumption penalty. However, one drawback of this method is an increase in hydrocarbon and carbon monoxide emissions, but these emissions are relatively easy to control by using a diesel oxidation catalyst (DOC).

Water can be introduced to the combustion chamber either through a separate water injector, or mixed with the fuel as a water-fuel emulsion.

Water injection imposes technical and regulatory problems. It requires a separate injection system with its own reservoir, injection lines, pump and injectors, all of which must be designed to withstand problems related to corrosion, deposits from dissolved impurities such as calcium carbonate and freezing in winter. Also, water injection requires the engine operator to refill the water reservoir periodically. However, the engine can function normally without the water and therefore, there is little or no incentive for the operator to comply with this requirement making the enforcement difficult.

Water-fuel emulsions have been considered the most effective way of introducing water into the engine cylinder. Several companies hold patents on emulsifying technologies that utilise chemical additives (surfactants), high pressures or electrical phenomena. Technologies, which are currently under development, appear to be using 20% to 30% of water in the emulsion. Water-fuel emulsions have altered fuel lubricity and corrosion properties that need to be considered as well as emulsion stability.

The California Air Resources Board (CARB) has certified Puri $NO_x$, a blend of diesel fuel with 20% water, as an alternative fuel aimed at the fleet market. However, concerns over corrosion and emulsion stability have not yet been resolved. Puri $NO_x$ achieves a 14% reduction in $NO_x$ and a 63% reduction in PM, but is associated with 15% loss in overall power. Lubrizol and Caterpillar are currently undertaking development work in this area.

### 5.4.2 Carbon-neutral Fuel

Carbon-neutral fuel is synthetic fuel—such as methane, gasoline, diesel fuel or jet fuel—produced from renewable or nuclear energy used to hydrogenate waste carbon dioxide recycled from power plant flue exhaust gas or derived from carbonic acid in seawater. Such fuels are potentially carbon neutral because they do not result in a net increase in atmospheric greenhouse gases. To the extent that carbon neutral fuels displace fossil fuels, or if they are produced from waste carbon or seawater carbonic acid, and their combustion is subject to carbon capture at the flue or exhaust pipe, they result in negative carbon dioxide emission and net carbon dioxide removal from the atmosphere, and thus constitute a form of greenhouse gas remediation. Such carbon-neutral and negative fuels can be produced by the electrolysis of water to make hydrogen used in the Sabatier reaction to produce methane which may then be stored to be burned later in power plants as synthetic natural gas, transported by pipeline, truck, or tanker ship, or be used in gas to liquids processes such as the Fischer-Tropsch process to make traditional transportation or heating fuels.

Carbon-neutral fuels have been proposed for distributed storage for renewable energy, minimizing problems of wind and solar intermittency, and enabling transmission of wind, water, and solar power through existing natural gas pipelines. Such renewable fuels could alleviate the costs and dependency issues of imported fossil fuels without requiring either electrification of the vehicle fleet or conversion to hydrogen or other fuels, enabling continued compatible and affordable vehicles. Germany has built a 250-kilowatt synthetic methane plant which they are scaling up to 10 megawatts. Audi has constructed a carbon neutral liquefied natural gas (LNG) plant in Werlte, Germany. The plant is intended to produce transportation fuel to offset LNG used in their A3 Sportback g-tron automobiles, and can keep 2,800 metric tons of $CO_2$ out of the environment per year at its initial capacity. Other commercial developments are taking place in Columbia, South Carolina, Camarillo, California, and Darlington, England.

The least expensive source of carbon for recycling into fuel is flue-gas emissions from

fossil-fuel combustion, where it can be extracted for about US $7.50 per ton. Automobile exhaust gas capture has also been proposed to be economical but would require extensive design changes or retrofitting. Since carbonic acid in seawater is in chemical equilibrium with atmospheric carbon dioxide, extraction of carbon from seawater has been studied. Researchers have estimated that carbon extraction from seawater would cost about $50 per ton. Carbon capture from ambient air is more costly, at between $600 and $1,000 per ton and is considered impractical for fuel synthesis or carbon sequestration.

Nighttime wind power is considered the most economical form of electrical power with which to synthesize fuel, because the load curve for electricity peaks sharply during the warmest hours of the day, but wind tends to blow slightly more at night than during the day. Therefore, the price of nighttime wind power is often much less expensive than any alternative. Off-peak wind power prices in high wind penetration areas of the U.S. averaged 1.64 cents per kilowatt-hour, but only 0.71 cents/kWh during the least expensive six hours of the day. Typically, wholesale electricity costs 2 to 5 cents/kWh during the day. Commercial fuel synthesis companies suggest they produce fuel for less than petroleum fuels when oil costs more than $55 per barrel. The U.S. Navy estimates that shipboard production of jet fuel from nuclear power would cost about $6 per gallon. While that was about twice the petroleum fuel cost in 2010, it is expected to be much less than the market price in less than five years if recent trends continue. Moreover, since the delivery of fuel to a carrier battle group costs about $8 per gallon, shipboard production is already much less expensive. However, U.S. civilian nuclear power is considerably more expensive than wind power. The Navy's estimate that 100 megawatts can produce 41,000 gallons of fuel per day indicates that terrestrial production from wind power would cost less than $1 per gallon.



### 5.4.3 Rape Methyl Ester (RME)

ape Methyl Ester (RME) produced from oil seed rape has a similar consistency to mineral diesel and is often referred to as biodiesel. Tailpipe emissions from a biodiesel vehicle can be similar to that of mineral diesel vehicles. However, during the fuels production and use lifecycle (well-to-wheel), there may be global environmental advantages. For example, when RME is burnt in a vehicle, the $CO_2$ emissions could be considered $CO_2$ neutral. The argument being that the $CO_2$ released during combustion is in balance to the $CO_2$ that was absorbed from the atmosphere during the life of the plant.

Many of the arguments put forward describing the $CO_2$ neutrality and renewable nature of RME and other biodiesel fuels are difficult to substantiate when scrutinised closely and all the effects (e.g. of pesticides, fertilisers and processing energy) are considered.

Interest in the use of alternative fuels such as natural gas (CNG and LNG), liquid petroleum gas (LPG) Methyl ethers (RME, DME) and alcohols (ethanol, methanol) has grown in parallel with the increasingly stringent emissions legislation. These fuels can have local emissions

advantages over diesel engines, particularly the gaseous fuels. But there are some disadvantages, as shown in Table 5.3.

**Table 5.3 Summary of the Advantages and Disadvantages of Alternative Fuels**

| Fuel | Advantages | Disadvantages |
|---|---|---|
| Natural Gas<br>(CNG. LPG) | Low CO, HC and $NO_x$ emissions<br>Can be renewable | High cost<br>Poor range<br>Difficult refuelling |
| Electricity | Potential for zero emissions<br>Power station emissions easier to control | Poor vehicle range/performance<br>Refuelling difficulties<br>High cost |
| LPG | Cheaper Fuel<br>Lower CO and HC emissions<br>Relatively widely available | Limited supply<br>Cost will rise with demand<br>Can have high $NO_x$ emissions |
| Methanol | Low CO and $NO_x$ emissions<br>Can be made from renewable sources | Lower vehicle range<br>Availability of fuel<br>Complexity of system |
| Ethanol | Low CO and $NO_x$ emissions<br>Can be made from renewable sources | Lower vehicle range<br>Availability/cost of fuel<br>Complexity of system |
| Rape Methyl Ether<br>(RME) | $CO_2$ neutral<br>Renewable | Energy intensive<br>Availability<br>Corrosive |
| Dimethyl Ether<br>(DME) | Low Emissions<br>Can be obtained from renewable sources | Limited supply<br>Complexity of system |
| Hydrogen | No $CO_2$, CO, PM or HC emissions<br>High Thermal efficiencies | High $NO_x$ emissions<br>Storage problems<br>Refuelling Infrastructure |



## 5.5 Barriers Facing Alternative Fuels

Every alternative fuel imposes some combination of increased capital costs, operating costs, technical challenges, or institutional issues as compared with diesel fuel. Barriers that have inhibited greater use of alternative fuels in public transportation vehicles include:

- Higher capital costs of alternative fuel vehicles and supporting facilities, especially natural gas facilities and electrification of routes for trolley buses or commuter rail lines;
- Higher operating costs for items like the alternative fuels themselves and maintaining vehicles and equipment using them;
- Unproven reliability and durability of early production models of new alternative fuel vehicles that could affect transit service dependability;
- Limited availability of new alternative fuels;
- Risk of interruptions in fuel delivery;

- The need to develop, adopt and enforce codes and standards for alternative fuel performance and stability, comparable to those used in specifying diesel fuel quality;
- Higher logistics costs of adding a duplicative inventory of components and spare parts peculiar to the alternative fuel vehicles; and,
- Costs of developing new operating and maintenance procedures for handling alternative fuels and conducting special training for mechanics and vehicle operators.

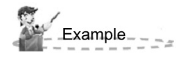


**Questions**

1. What is the alternative energy?
2. What are the advantages and disadvantages of hydrogen?
3. What is carbon-neutral fuel and how is it produced?
4. What is the advantage of propane autogas compared with traditional fuels?
5. Please sum up the process of the acquisition of diethyl ether.

# Chapter 6

# The Reduction of Gasoline Engine Emissions




The increasing number of car production in China is as shown in Figure 6.1. However, China's V emission standard for new vehicles will come to effect in the whole country in 2017. The new standard aims to limit the number of old vehicles on the road and enforce a higher emission level for new vehicles in the city. Vehicles that meet China's V standard will have lower nitrogen oxide, carbon monoxide and hydrocarbon emission.

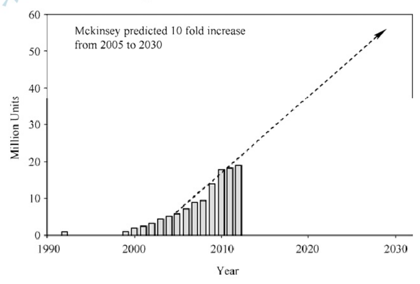
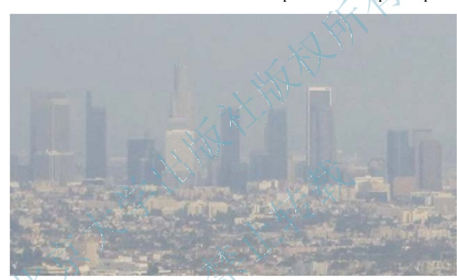



**Figure 6.1 Car production in China**

Question: What can we do to improve the emission of gasoline engine ?

## 6.1 Current Status

The world-wide concern over environmental pollution with respect to the gasoline engine began in the early 1940s when Los Angeles residents became aware of an atmospheric phenomenon known as photochemical smog, as shown in Figure 6.2. The smog formation resulted from reaction between nitrogen oxides and hydrocarbons, producing harmful lachrymatory compounds. These were retained in the Los Angeles basin by a temperature inversion in the upper atmosphere preventing dispersion of the pollutants, causing smog formation. Although Los Angeles represents a specific problem due to climatic conditions peculiar to the area, the smog formation focused attention in the United States on all aspects of atmospheric pollution.

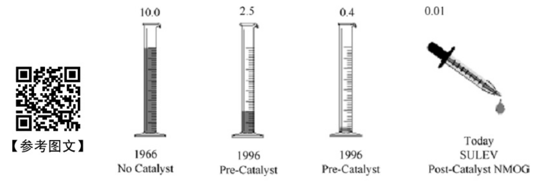


【参考图文】

**Figure 6.2 Smog in the Los Angeles**



Current tailpipe regulations for gasoline engines focus on carbon monoxide (CO), the oxides of nitrogen (collectively called $NO_x$) and hydrocarbons (HC). These standards have become increasingly stringent since their introduction in the 1960's. This is demonstrated in Figure 6.3, which shows the change in HC emissions from gasoline powered vehicles in the United States since 1966.




【参考图文】

**Figure 6.3 HC emission standards have changed dramatically**

Historically, gasoline engines have had more relaxed emission standards. Many countries are applying more severe gasoline standards to vehicles, with other regulatory bodies following suit in the next few years.

Evaporative emissions standards consider the emission of fuel vapor from the vehicle during operation and while parked. The zero emissions vehicle (ZEV) standards recently introduced in California are so severe that evaporative emissions from the fuel system must approach zero grams.

Each of these regulations provides a control challenge on its own, but when combined with other regulations and system objectives, such as fuel economy and performance, the challenges become significant. And, the composition of the exhaust gases varies significantly for gasoline and diesel engines; and differences in operating conditions affect the performance of potential aftertreatment devices. As such, control of emissions from these two types of automotive engines is handled in very different ways.



## 6.2 Tailpipe Emission Control

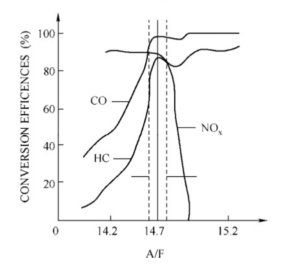
### 6.2.1 Gasoline Engines

In conventional port fuel injection (PFI), gasoline engines, fuel is injected into the intake port of each cylinder, where it combines with air. The air fuel mixture is inducted into the cylinder and ignited. Spark ignited (SI) engines typically operate with air to fuel ratio (A/F) ranging from 12:1 to 18:1. Engine out emissions vary over this A/F range, with HC and CO highest at rich conditions and $NO_x$ emissions peaking near an A/F of 16:1.

A three-way catalyst (TWC) is widely used to simultaneously convert emissions of CO, HC and $NO_x$ from an SI engine. Conversion occurs via catalysis over a precious metal, typically Pt and/or Pd, and is highly dependent on the A/F of the exhaust gas. As demonstrated in Figure 6.4, useful conversion efficiency for all three species occurs only in a narrow band about stoichiometric A/F, which is near 14.6:1 for typical formulations of gasoline. This narrow band can be widened slightly via A/F modulation, but A/F control remains critical to effective emissions control with a TWC, as shown in Figure 6.4.

#### 6.2.1.1 A/F Control

A/F is typically controlled with fuel via implementation of feed forward (open loop) control, in addition to feedback utilizing an exhaust gas oxygen sensor (EGO) located upstream of the TWC. The feed forward control is critical in this approach since the feedback signal is delayed by several engine cycles due to gas transport and sensor dynamics, and the EGO sensor is unreliable when cold.





【参考视频】

**Figure 6.4　TWC conversion efficiency varies with A/F. Efficient simultaneous conversion of CO,HC and $NO_x$ occurs only near stoichiometry**

The most common approach to feed forward control is a calculation of fuel from desired A/F and an estimate of cylinder air charge. On-line implementation of an air charge model is typically based on either measurement of air flow rate or intake manifold pressure. A block diagram of a typical air flow meter based approach is given in Figure 6.5. Compensation for nonlinearities and sensor dynamics, such as air charge maldistribution and air flow meter dynamics, is included in many applications.

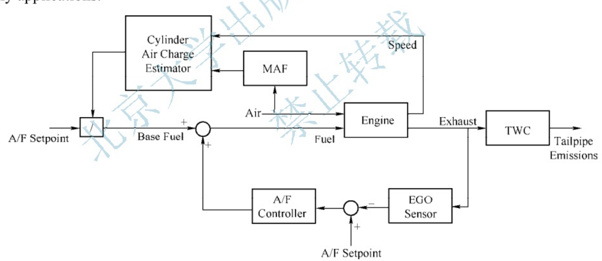





**Figure 6.5　This schematic represents a typical A/F control algorithm. In this case, feed forward control is based on an air flow meter measurement and feedback is implemented with a HEGO sensor**

Feedback control of fuel is typically implemented with a switching EGO sensor (sometimes referred to as a HEGO, if heated). This sensor simply reports whether the exhaust gas is lean or rich; the magnitude of the deviation from stoichiometry is unknown. In most cases, the feedback control is a conventional proportional plus integral (PI) algorithm. This approach has been very successful for the last two decades. Decreasing emission standards, however, continue to push sensor and control technology.

Some implementations now utilize a universal EGO(UEGO), which is a linear exhaust

oxygen sensor providing an output proportional to A/F over a wide range. More advanced control methods and architectures have been explored, with some considering use of multiple HEGO and/or UEGO sensors for A/F control. Nonlinear fuel dynamics add significant uncertainty to the A/F control problem. Some of the fuel injected in the port impacts the wall, forming a puddle and affecting the amount of fuel entering the cylinder. To complicate matters, the dynamics vary with fuel properties, aging and other factors. As such, adaptive, transient compensation of this effect is important to effective A/F control over the life of the vehicle. One approach to this difficult problem is using a switching EGO sensor.

Considerable effort is made to minimize engine out emissions to reduce the amount of costly precious metal required in the TWC. A common method for $NO_x$ reduction is recirculation of exhaust gases (EGR), which lowers combustion temperatures to conditions where less $NO_x$ is produced. EGR can be introduced externally to the engine, via a valve that connects the intake and exhaust manifolds, or directly via control of intake and/or exhaust valve timing. EGR displaces fresh air in the cylinder at a given operating condition and must be accounted for in the estimation of air charge. Estimation of EGR is difficult, however, due to the unsteady flow conditions in the exhaust and durability of sensors in the harsh exhaust environment. This adds to the uncertainty associated with air charge estimation and A/F control, in general.

Uncertainty prevents precise control of A/F, leading to departures from stoichiometry. Steady state variation is managed with feedback control. Brief transient deviations are enabled by the oxygen storage behavior of the TWC. Ceria is added to the TWC to provide the capability to store a limited amount of oxygen for release when needed to complete oxidation reactions. The dynamics introduced by this behavior complicate control and TWC models including oxygen storage dynamics are critical to effective control development.



#### 6.2.1.2 Cold Start

Another challenging aspect of the TWC is its sensitivity to temperature. In fact, the TWC is considered ineffective at low temperatures, as it does not efficiently convert CO, $NO_x$ or HC. Cold start emissions of HC and CO account for more than 80% of the total HC and CO emissions over common test cycles. Conversion efficiencies increase with temperature and the condition commonly referred to as “light off” occurs when HC conversion efficiency reaches 50%.

Warming the TWC more rapidly is one approach to improvement. A common control methodology for catalyst heating is aggressive spark retard, which increases the specific heat flow to the exhaust. This moves ignition from the optimal torque condition, increasing fuel usage and can increase engine out HC emissions. These competing objectives lead to a tradeoff requiring optimization for full benefit. In advanced technology engines, where fuel is injected directly into the cylinder, at least one additional injection can be made prior to ignition to enable more aggressive spark retard for improved heating.

Another approach to reducing cold start emissions is reduction of engine out emissions while

cold. For example, variable valve timing can be used to improve HC emissions at low temperature. Optimum intake valve timing can reduce wall wetting and improve mixture preparation, while control of exhaust valve timing can improve secondary burning of HC and heat flow to the exhaust.

#### 6.2.1.3 partially zero emissions vehicle (PZEV)

California has legislated particularly aggressive emission regulations with the partially zero emissions vehicle (PZEV) standards. Achievement of these very low emissions is a formidable challenge, particularly when combined with fuel economy, vehicle performance and cost constraints.

As discussed earlier, the majority of tailpipe emissions occur during cold-start. As such, PZEV efforts are highly focused in this area. In some applications, the engine is operated rich with aggressive spark retard, producing significant CO and HC. Secondary air is injected into the exhaust path, providing the oxygen necessary for oxidation of these species. The large exotherm created by these reactions significantly improves the catalyst light off time.

In addition to several engine hardware and catalyst actions, such as introduction of charge motion control devices and increased TWC cell density, sensor modifications are also considered. For example, a fast light off HEGO, which reaches operating temperature very quickly, or a UEGO may replace the conventional HEGO sensor. Additional HEGO or UEGO sensors may also be added at other locations in the exhaust path to improve performance of sophisticated A/F control algorithms, for example fore-aft oxygen storage control.



#### 6.2.1.4 Lean Burning Gasoline Engines

Some advanced technology engines operate lean of stoichiometry to take advantage of improved fuel economy via reduction in pumping loss and enhanced thermal efficiency. PFI engines can be designed to operate with their homogeneous mixture at A/F near 20:1. Direct injection spark ignition (DISI) engines can operate at very lean conditions, potentially 60:1 or higher depending on the combustion system design. This very lean operation occurs during stratified combustion, when fuel is injected late in the compression stroke to form a small region of near stoichiometric mixture near the spark plug. The remainder of the cylinder is filled primarily with fresh air, forming an overall mixture that is very lean.

As seen in Figure 6.4, conversion of $NO_x$ by the conventional TWC is not efficient at lean conditions. Therefore, another catalyst specifically aimed at $NO_x$ conversion at lean conditions is added. A Lean $NO_x$ Trap (LNT) is currently the preferred approach.

Storage capacity of a typical LNT, as shown in Figure 6.6, is high only in a relatively narrow temperature window. The size and location of the temperature window varies with catalyst formulation, but an efficient operating temperature is generally in the neighborhood of 300—350℃. Passive control of exhaust gas temperature limits the operating conditions at which the engine can

operate lean. Active control with an exhaust gas heat exchanger and/or flow diversion device adds complexity, but can potentially lower overall system cost if the quantity of precious metal in the catalyst can be reduced.

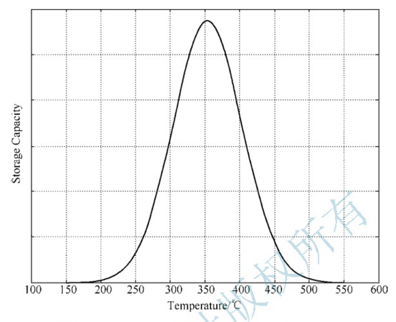



**Figure 6.6 LNT storage capacity is highly dependent upon temperature**



As the name suggests, the LNT stores $NO_x$; and it must be periodically regenerated by exposure to rich conditions. These frequent transitions from lean to rich operation must not be perceptible by the driver, making torque management a critical control feature. This control problem is especially challenging in DISI engines, where this transition entails switching to and from stratified operating conditions.

Regeneration, frequently referred to as purge, must be carefully controlled to avoid emissions breakthrough. Purge frequency and duration, as well as the A/F profile during purge are key control variables.

Knowledge of the storage state of the LNT is critical to effective control, particularly for decisions regarding purge initiation. Since the storage state cannot be directly measured, models are key components of an LNT control strategy. Some control schemes rely on models of incoming and breakthrough $NO_x$ to determine the state of the LNT . Others utilize a $NO_x$ sensor downstream of the LNT to measure $NO_x$ breakthrough for initiation of purge. These methods also require estimation of incoming $NO_x$ to ascertain the state of the LNT.

End of purge is typically detected with an EGO sensor, either HEGO or UEGO. The oxygen sensor senses reductant breakthrough with a rich reading, indicating that conversion is nearly complete. Reductant breakthrough contributes to CO and HC emissions. Therefore models are often utilized in control in an effort to end purge before breakthrough occurs.

Optimization of purge frequency and duration requires sophisticated techniques due to the LNT storage element. Linear programming methods commonly used for optimization of engine

operating conditions are not applicable. The dynamic programming approach presented in is an excellent solution provided in a framework accessible to development engineers.

Another factor that must be considered in LNT control is the effect of sulfur. Sulfur is found in most fuels and sulfur oxides ($SO_x$) are a component of combustion gases. The presence of $SO_x$ at the LNT results in formation of high temperature stable sulfates, which deplete $NO_x$ storage capacity. Regeneration, referred to as de$SO_x$, requires exposure to high temperatures. Spark retard and/or lean rich cycling are common methods to increase exhaust gas temperatures to the levels required for de$SO_x$. Initiation of de$SO_x$ is dependent upon knowledge of the state of the LNT, with modeling again playing a key role in the control strategy.

Thermal durability of the LNT is another challenge. LNT storage capacity reduces with time and the effects of thermal aging are not recoverable. Therefore, adaptation is important to effective $NO_x$ control over the lifetime of the vehicle.

#### 6.2.1.5 The electronic control system

In practice, the electronic control system (shown in Figure 6.7) has to be more complex than might be assumed from the preceding paragraph. When the engine is being cranked for starting it has to switch automatically from a closed- to an open-loop system, to provide a rich mixture. In this condition the air supply for the second converter bed is diverted to the exhaust manifold to oxidise the inevitable HC and CO content, thus avoiding a rapid rise in temperature in, and overloading of, the second stage of the converter. Owing to the low temperatures in the combustion chambers of the engine, $NO_x$ production is minimal or even zero, so no conversion is required in the first stage.



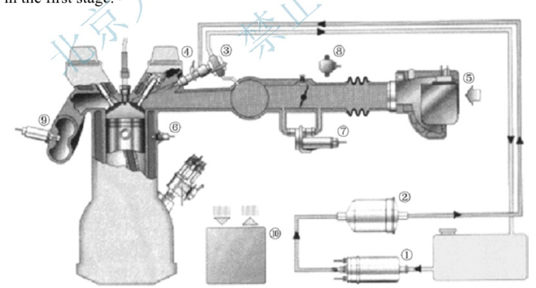



**Figure 6.7 The electronic control system**

①—fuel tank; ②—fule filter; ③—fuel pressure regulator; ④—injector; ⑤—air filter; ⑥—water temperature sensor; ⑦—ilder control valve; ⑧—ail mass-flow sensor; ⑨—oxygen sensor; ⑩—ECU controller

During warm-up the mixture strength has to be modified for the transition from rich to

stoichiometric mixture. However, to cater for heavy loading, such as acceleration uphill, it may again have to be enriched, perhaps with exhaust gas recirculation in this condition to inhibit the formation of $NO_x$. The on-board microprocessor capabilities, therefore, must include control over idle speed, spark timing, exhaust gas recirculation, purge of hydrocarbons from carbon canister vapour-traps, early evaporation of fuel by air intake heating, torque converter lock-up, and a fault-diagnosis system.

#### 6.2.1.6 Warm-air intake systems

Apart from setting the coolant thermostat to open at higher temperatures to improve combustion in cold conditions, several manufacturers have introduced automatic control of the temperature of the air drawn into the carburetor. The General Motors system is built into a conventional air cleaner. There are two air valves, operated by vacuum-actuated diaphragm mechanisms, and controlled by a thermostat. One valve lets warm and the other cold air into the intake.

The thermostat, mounted on the air cleaner, senses the temperature inside, maintaining it at 40℃ to 45℃. This thermostat operates a two-way control valve directing either induction system depression or atmospheric pressure to the actuator, according to whether cool or warm air is required. The warm air is taken from a jacket around the exhaust manifold.

Ford has developed a similar system. In this case, however, the thermostat senses under-bonnet temperature, and provision is made, by means of a vacuum-actuated override, to enable maximum power output to be obtained during warm-up.

The Austin-Rover design is outstanding for its simplicity. It is a banjo shaped pressed steel box assembly, the handle of which is represented by the air intake duct to the air cleaner. In both the upper and lower faces of the box is a large diameter port, and a flap valve is poised between them. This flap valve is mounted on a bimetal strip which, when hot, deflects to close one port and, when cold, to close the other. The latter port simply lets air at the ambient temperature into the intake, while the former is connected by a duct to a metal shroud over the exhaust manifold and therefore passes hot air into the intake. It follows that the temperature of the incoming mixture from both ports is regulated by its effect on the bimetal strip, which deflects the flap valve towards the hot or cold port, as necessary.

#### 6.2.1.7 Gasoline direct injection

Gasoline Direct Injection (GDI), also known as Petrol Direct Injection, Direct Petrol Injection, Spark Ignited Direct Injection (SIDI) and Fuel Stratified Injection (FSI), is a variant of fuel injection employed in modern two-stroke and four-stroke gasoline engines, as shown in Figure 6.8. The gasoline is highly pressurized, and injected via a common rail fuel line directly into the combustion chamber of each cylinder, as opposed to conventional multi-point fuel injection that injects fuel into the intake tract, or cylinder port. Directly injecting fuel into the combustion chamber requires high pressure injection whereas low pressure is used injecting into the intake tract or cylinder port.



Figure 6.8 GDI engine

【参考视频】

In some applications, gasoline direct injection enables a stratified fuel charge (ultra lean burn) combustion for improved fuel efficiency, and reduced emission levels at low load.

The major advantages of a GDI engine are increased fuel efficiency and high power output. Emissions levels can also be more accurately controlled with the GDI system. The cited gains are achieved by the precise control over the amount of fuel and injection timings that are varied according to engine load. In addition some engines operate on full air intake. That is, there is no air throttle plate eliminating air throttling losses in some GDI engines, when compared with a conventional fuel-injected or carbureted engine, which greatly improves efficiency, and reduces piston "pumping losses". Engine speed is controlled by the engine control unit/engine management system (EMS), which regulates fuel injection function and ignition timing, instead of having a throttle plate that restricts the incoming air supply. Adding this function to the EMS requires considerable enhancement of its processing and memory, as direct injection plus the engine speed management must have very precise algorithms for good performance and drivability.

Direct injection may also be accompanied by other engine technologies such as turbocharging or supercharging, variable valve timing (VVT) or continuous variable cam phasing, and tuned/multi path or variable length intake manifolding (VLIM, or VIM). Water injection or (more commonly) exhaust gas recirculation (EGR) may help reduce the high nitrogen oxides ($NO_x$) emissions that can result from burning ultra lean mixtures; modern turbocharged engines use continuous cam phasing in place of EGR.

In 2013, a research found that although gasoline direct injection engines dramatically reduce $CO_2$ emissions, they release about 1,000 times more particles classified by the World Health Organization as harmful than traditional petrol engines and 10 times more than new diesel engines. The release happens because direct injection results in uneven burning of fuel due to uneven mixing of fuel and air (stratification) and because direct injection engines operate with a higher pressure in their cylinders than the older engines.

This pollution can be prevented with a relatively inexpensive filter that can significantly reduce the emissions of particles. However, fitting the filter is not mandatory yet.

### 6.2.2 Aftertreatment

Low emissions demand that aftertreatment systems operate immediately after starting the

engine. High activity catalyst formulations have low temperature light-off, and when combined with effective heat and mass transfer and low heat capacity, respond quickly. Mounting the catalyst close to the manifold (close-coupled) minimizes the time the catalyst takes to reach working temperature.

#### 6.2.2.1 Catalytic conversion

A catalytic conversion is an emission control device that converts toxic pollutants in exhaust gas to less toxic pollutants by catalyzing a redox reaction (oxidation or reduction). Catalytic converters are used with internal combustion engines fueled by either petrol (gasoline) or diesel—including lean-burn engines as well as kerosene heaters and stoves.

At this point while some other manufacturers were promoting the lean-burn concept as the way Forward, GM engineers, accepting the penalty of low octane number, opted for unleaded fuel and catalytic conversion for meeting regulations on both emissions and fuel economy, while avoiding adverse effects on engine durability. As a first step, all their car engines were designed for fuel rated at 91 Motor Octane Number, mainly by reducing compression ratios and modifying the valves and their seats.

They argued that unleaded fuel offers several benefits: first, the major source of particulate emissions, lead oxyhalide salts, is eliminated; secondly, there is a consequent reduction in combustion chamber deposits, which have the effect of thickening the boundary layers in the gas in the combustion chamber and this, by quenching them, encourages the formation of HC; thirdly, a further reduction in HC is obtained because of the additional oxidation that occurs in the exhaust system owing to the absence of lead additives and also because the lead salt deposits tend to cause deterioration of the $NO_x$ control system by adversely affecting the flow characteristics of the EGR orifices; fourthly, maintenance of spark plugs, exhaust systems and the frequency of changing lubricating oil are all reduced by the elimination of the lead salts, as also of course is the generation of acids by the halide scavengers that have to be used with them; finally, because catalytic converters call for unleaded fuels controversy over the alleged toxic effects of lead salts in the environment was neatly side-stepped.

#### 6.2.2.2 Two-way catalytic conversion

This type of catalytic converter is widely used on diesel engines to reduce hydrocarbon and carbon monoxide emissions. They were also used on gasoline engines in American- and Canadian-market automobiles until 1981. Because of their inability to control oxides of nitrogen, they were superseded by three-way converters. However, two-way converters are still used for lean-burn engines.

A two-way (or "oxidation") catalytic converter has two simultaneous tasks:

(1)Oxidation of carbon monoxide to carbon dioxide: $2CO + O_2 \rightarrow 2CO_2$

(2)Oxidation of hydrocarbons (unburned and partially burned fuel) to carbon dioxide and water: $C_xH_{2x+2}+2+ [(3x+1)/2]\ O_2 \rightarrow xCO_2 + (x+1)\ H_2O$ (a combustion reaction)

The emissions regulations for the 2014 model year required reductions of 95% in HC, 89% in CO and 98% in $NO_x$ by comparison with 1990 levels. GM concluded that to meet these requirements while simultaneously improving not only economy but also drive ability, both of which had deteriorated severely as a result of emission control by engine modifications, two-way catalytic converters were needed. The term two-way conversion implies oxidation of the two constituents in the exhaust, HC and CO, to form $CO_2$ and $H_2O$. Such a converter therefore contains only oxidation catalysts and, moreover, without oxygen in the exhaust cannot function. Consequently, the air-fuel mixture supplied to the engine must be at least stoichiometric or, better still, lean. Incidentally, the earlier practice of feeding air into the exhaust was intended primarily for burning the excess hydrocarbons during the first five cycles of the test after a cold start with engines. It is unnecessary with the accurate regulation of air : fuel ratio by computer-controlled injection.

#### 6.2.2.3 The converter

Two-way catalytic converters comprise a container, usually of chromium stainless steel, and the catalysts and their supports, all enclosed in an aluminized steel heat shield. Initially, the alumina pellet type of support for the catalyst was the most favoured because it had been developed to an advanced stage in other industries. Figure 6.9. The stainless steel housing for monolithic catalyst carriers is enclosed in an aluminized steel outer casing. Sandwiched between top halves of the outer and inner shells is heat insulation material. The perforations in the lower half of the outer shell, termed the grass shield, facilitate local cooling.

Either platinum (Pt) alone or platinum and palladium (Pl) are used as catalysts. The cost of this noble metal content is of the order of 15 to 20 times that of the stainless steel shell that houses them, so other catalysts such as copper and chromium have been tried, with some success, but have not come into general use because they are prone to deterioration owing to attack by the sulphuric acid formed by combustion of impurities in the fuel. A typical two-way converter for an American car contains about 1.6g of noble metals in the Pt : Pl ratio of 5:2.




【参考图文】




**Figure 6.9 The stainless steel housing for monolithic catalyst carriers**

### 6.2.2.4 Catalyst support

Considerable development effort has been devoted to monolithic catalyst supports in the form of one-piece extruded ceramic honeycomb structures having large surface areas on to which the noble metal catalysts are deposited. Gas flow paths through them are well defined and their mass is smaller than that of the pellet type, warming up more rapidly to their working temperature of about 550°C. In some applications, for ease of manufacture two such monoliths are installed in tandem in a single chamber, as shown in Figure 6.10.





**Figure 6.10 Two monolithic catalyst carriers being assembled in series into their casing**

Pellet systems are, nevertheless, widely employed in the USA for trucks, where compactness is not an overriding requirement but durability under extremely adverse conditions is. The pellets are relatively insensitive to thermal stress because they can move to relieve it. Moreover, the hottest part of such a bed is near its centre, whereas that of a ceramic monolith is about 25 mm from its leading edge, accentuating thermal stress problems. Packaging for pellets, on the other hand, is more complex, so both assembly and servicing of the monolithic type are easier.

### 6.2.2.5 Metallic monoliths for catalytic converters

Another important aim is of course durability at both very high and rapidly changing temperatures. Ceramics do not satisfy all these requirements, so efforts were directed at producing acceptable metallic matrices. These offer advantages of compactness, minimum back-pressure in the exhaust system, rapid warm-up to the minimum effective operating temperature (widely termed the light-off temperature) which, for this type of monolith, is claimed to be about 250℃.

Two obstacles had to be overcome. First was the difficulty of obtaining adequate corrosion resistance with the very thin sections needed for both compactness and acceptably low

back-pressure. Secondly, it was difficult to join the very thin sections while retaining the robustness necessary to withstand the severe thermal loading and fatigue.

These problems had been solved by Emitec, a GKN-Unicardan company in Germany. They had developed a special stainless steel alloy, called Emicat, which they used in foil strips only 0.04 mm thick to construct the catalyst carriers in monolithic form. These are now made up into matrices comprising alternate plain and corrugated strips, wound in an S-form, as shown in Figure 6.11. The matrices are inserted into steel casings and the whole assembly joined by a patented high temperature brazing process. Form matrices proved to be more durable than spirally wound cylindrical units.

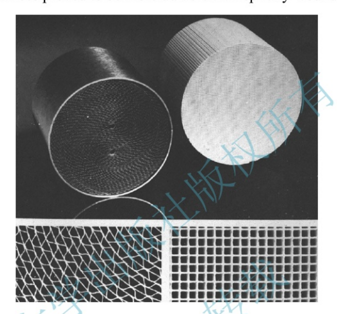


**Figure 6.11 Comparison between ceramic and metallic monoliths**



Emicat is an Fe, 20% Cr, 5% Al, 0.05% Y alloy. Yttrium, chemical symbol Y, has a melting point of 1250°C. It is a metal but with a strong chemical resemblance to rare earths, with which it therefore is usually classified. Its oxide, $Y_2O_3$, forms on the surface of the foil and protects the substrate from further oxidation. At a content of 0.05% yttrium is very effective in enabling the alloy to withstand not only temperatures of up to 1100°C over long periods, but also the higher peaks that can be attained in catalytic converters in the event of a malfunction of the ignition system. Even better protection, however, can be obtained by increasing it up to 0.3%, though at higher cost.

The advantages obtained with the monoliths made of Emicat include: rapid warm-up; resistance to both thermal shock and rapid cyclical temperature changes up to well over 1300°C (both due to the good thermal conductivity of the material and low heat capacity of the assembly); minimal back-pressure, by virtue of the thin sections of the catalyst carrier foil; compactness due to thinness of the sections and the absence of the mat needed around a ceramic monolith (to absorb its thermal expansion); large area of the catalyst exposed to the gas flow (owing to the high surface: volume ratio of the foil); and avoidance of local overheating, by virtue of both the compactness of the unit and the good thermal conductivity of the metal as compared with that of ceramic; and, finally, because the complete unit is directly welded into the exhaust system, the

costs of assembling ceramic monoliths and their wire mesh or fibre mat elastic supports into their cans are avoided. The properties of the two types of converter are set out in Table 6.1.

**Table 6.1 METAL AND CERAMIC MONOLITH MATERIALS COMPARED**

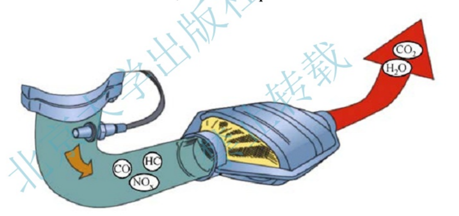
| Property | Metal | Ceramic |
|---|---|---|
| Wall thickness, mm | 0.04 | 0.15～0.2 |
| Cell density, cell/in$^2$ | 400 | 400 |
| Clear cross-section, % | 91.6 | 67.1 |
| Specific surface area, m$^2$/l | 3.2 | 2.4 |
| Thermal conductivity, W/m K | 14～22 | 1～1.08 |
| Heat capacity, kJ/kg K | 0.5 | 1.05 |
| Density, g/cm$^3$ | 7.4 | 2.2～2.7 |
| Thermal expansion, $\Delta L/L$, $10^{-6}$K | 15 | 1 |

Note: Thicknesses and cross-sections are of metals uncoated with catalyst

### 6.2.2.6 Three-way catalytic converters

Three-way catalytic converters (TWC) (See Figure 6.12)have the additional advantage of controlling the emission of nitric oxide and nitrogen dioxide (both together abbreviated with $NO_x$ and not to be confused with nitrous oxide), which are precursors to acid rain and smog.







【参考视频】

**Figure 6.12 Three-way catalytic converters**

Since 1981, “three-way” (oxidation-reduction) catalytic converters have been used in vehicle emission control systems in the United States and Canada; many other countries have also adopted stringent vehicle emission regulations that in effect require three-way converters on gasoline-powered vehicles. The reduction and oxidation catalysts are typically contained in a common housing; however, in some instances, they may be housed separately. A three-way catalytic converter has three simultaneous tasks:

1. Reduction of nitrogen oxides to nitrogen and oxygen: $2NO_x \rightarrow xO_2 + N_2$

2. Oxidation of carbon monoxide to carbon dioxide: $2CO + O_2 \rightarrow 2CO_2$

3. Oxidation of unburnt hydrocarbons (HC) to carbon dioxide and water: $C_xH_{2x+2}$ + $[(3x+1)/2]O_2 \rightarrow xCO_2 + (x+1)H_2O$.

These three reactions occur most efficiently(as shown in Figure 6.13) when the catalytic





converter receives exhaust from an engine running slightly above the stoichiometric point. For gasoline combustion, this ratio is between 14.6 and 14.8 parts air to one part fuel, by weight. The ratio for autogas (or liquefied petroleum gas LPG), natural gas and ethanol fuels is slightly different for each, requiring modified fuel system settings when using those fuels. In general, engines fitted with 3-way catalytic converters are equipped with a computerized closed-loop feedback fuel injection system using one or more oxygen sensors, though early in the deployment of three-way converters, carburetors equipped with feedback mixture control were used.

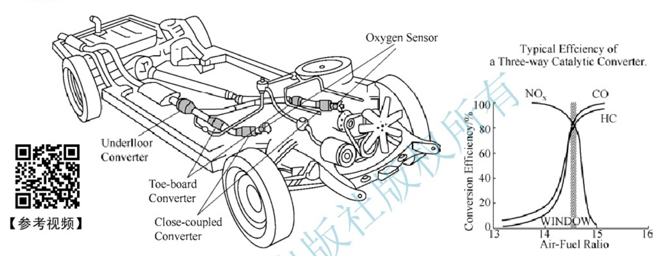



**Figure 6.13  Typical efficiency of a three-way Catalytic converter**



Three-way converters are effective when the engine is operated within a narrow band of air-fuel ratios near the stoichiometric point, such that the exhaust gas composition oscillates between rich (excess fuel) and lean (excess oxygen). Conversion efficiency falls very rapidly when the engine is operated outside of this band. Under lean engine operation, the exhaust contains excess oxygen, and the reduction of $NO_x$ is not favored. Under rich conditions, the excess fuel consumes all of the available oxygen prior to the catalyst, leaving only oxygen stored in the catalyst available for the oxidation function.

Closed-loop engine control systems are necessary for effective operation of three-way catalytic converters because of the continuous balancing required for effective $NO_x$ reduction and HC oxidation. The control system must prevent the $NO_x$ reduction catalyst from becoming fully oxidized, yet replenish the oxygen storage material so that its function as an oxidation catalyst is maintained. This entails installing an oxygen sensor in the exhaust, and an on-board microprocessor to exercise control, both to correct continuously for divergencies from the stoichiometric ratio and to ensure good driveability.

Three-way catalytic converters can store oxygen from the exhaust gas stream, usually when the air–fuel ratio goes lean. When sufficient oxygen is not available from the exhaust stream, the stored oxygen is released and consumed (see cerium(IV) oxide). A lack of sufficient oxygen occurs either when oxygen derived from $NO_x$ reduction is unavailable or when certain

maneuvers such as hard acceleration enrich the mixture beyond the ability of the converter to supply oxygen.

The additional catalytic bed contains Rhodium (Rh) for reduction of the oxides of nitrogen. An outcome was an increase to about 3g in the total noble metal content. In practice, with a 0.1% rich mixture, about 95% of the $NO_x$ can be removed by such a catalytic converter(as shown in Figure 6.14). A reducing atmosphere is essential so the mixture must not be lean, and therefore the conversion of $NO_x$ has to precede the oxidation of the HC and CO, as shown in Figure 6.15.

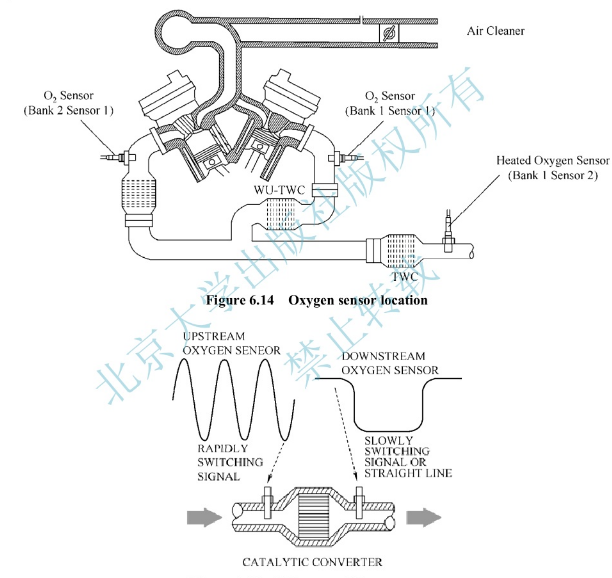



**Figure 6.14 Oxygen sensor location**



**Figure 6.15 Difference of Oxygen sensor**

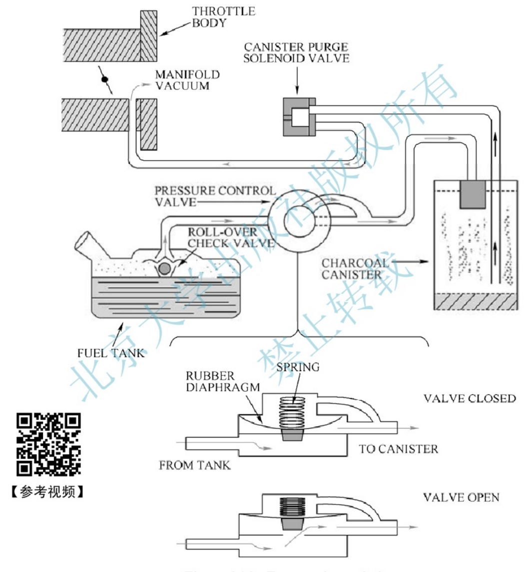


Oxygen released in the initial reduction process, in the Rh bed, immediately starts the second stage of the overall process while the exhaust gas is still in the first stage. The oxygen that remains unused then passes on into the Pt or Pt-Pl second stage of the converter, in a separate housing downstream of the first. Here extra air is supplied for completion of the oxidation. On the other hand, if what is termed a dual-bed converter is used, both stages are in a single housing, though in

separate compartments between which is sandwiched a third chamber into which the extra air is pumped, to join the gas stream before it enters the Pt, or Pt-Pl, stage.

## 6.3 Evaporative Emissions

The evaporative emissions(as shown in Figure 6.16) are mostly hydrocarbons though, with some special fuels and those that have been modified to increase octane number, alcohols may also be present. In general, the vapour comes from the sources—






【参考视频】

**Figure 6.16 Evaporative emission**

a. Fuel tank venting system;

b. Permeation through the walls of plastics tanks;

c. Through the crankcase breather.

Permeation through the walls of plastics tanks is controlled by one of four methods. These are—

a. Fluorine treatment;

b. Sulphur trioxide treatment;

c. Du Pont one-shot injection moulding ( a laminar barrier treatment) ;

d. Premier Fuel Systems method of lamination.

Plastics tanks are generally moulded by extrusion of what is termed a parison (a large-diameter tube) which is suspended in a female mould into which it is then blow-moulded radially outwards. The chemical treatments are applied internally, either in the parison or in the blow-moulding. With either procedure, problems arise owing to the toxicity of the barrier chemicals and in the disposal of the chemical waste.

A typical evaporative emission control system, as shown in Figure 6.17. When the PCM turns on the canister purge solenoid valve, manifold vacuum draws HC vapors from the canister into the engine. When the pressure control valve opens, fumes from the fueltank are vented into the charcoal canister and eventually into the engine.

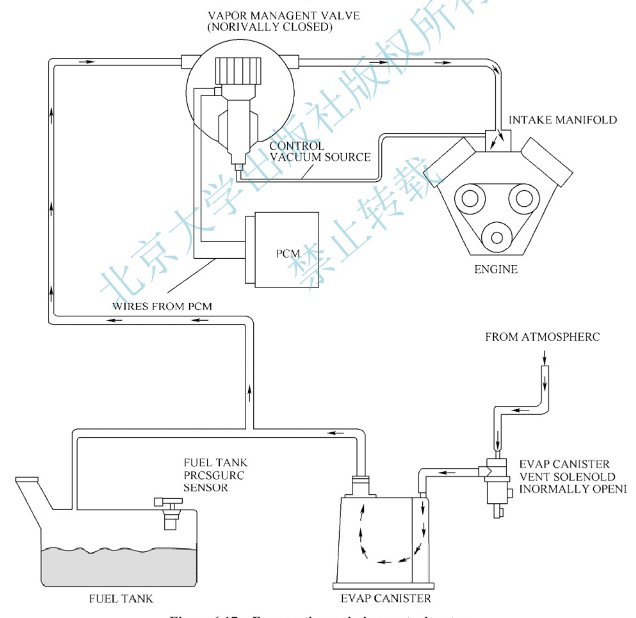



**Figure 6.17 Evaporative emission control system**

## 6.4 Crankcase Emission Control

About 55% of the hydrocarbon pollution is in the exhaust, crankcase emissions account for a further 25% and the fuel tank and carburettor evaporation makes up the other 20%. These figures, of course, vary slightly according to the ambient temperature. In general unburnt hydrocarbons from these two sources amount to no more than about 4%–10% of the total pollutants.

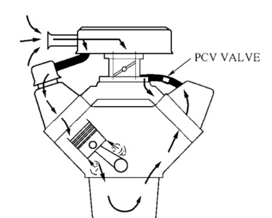



**Figure 6.18 positive ventilation system**

Crankcase fumes are drawn into the induction manifold by a closed circuit, positive ventilation system, as shown in Figure 6.18. One pipe is generally taken from the interior of the air filter to the rocker cover, and another from the crankcase to the induction manifold. Thus, air that has passed through a filter is drawn past the rocker gear into the crankcase and thence to the manifold, whence it is delivered into the cylinders, where any hydrocarbon fumes picked up from the crankcase are burnt.

There are three requirements for such a system: first, the flow must be restricted, to avoid upsetting the slow running condition; secondly, there must be some safeguard to prevent blow-back in the event of a backfire and, thirdly, the suction in the crankcase has to be limited. AC-Delco (See Figure 6.19) produce a valve for insertion in the suction line to meet these requirements.

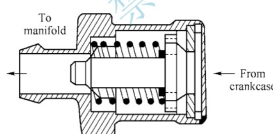



**Figure 6.19 AC-Delco crankcase ventilation control valve. With zero depression in the manifold, the valve seats on the right-hand orifice and with maximum depression on the left-hand one.**

It comprises a spring-loaded disc valve in a cylindrical housing. When there is no suction—engine off, or backfire condition—the valve seats on a port at one end, completely closing it. With high depression in the manifold, slow running or overrun, the valve seats on a larger diameter port at the other end, and a limited flow passes through the holes which, because they are near its periphery, are covered when it seats on the smaller diameter port. Flow through the larger port is restricted by the valve stem projecting into it. In normal driving, the valve floats in equilibrium between the two seats, and air can pass through the clearance around its periphery as well as through the holes.

Spring force, crankcase pressure, and intake manifold vacuum regulate the flow rate through the PCV valve in Figure 6.20(a). Air flows through the PCV valve during idle, cruising, and light-load conditions in Figure 6.20(b). Air flows through the PCV valve during acceleration and when the engine is under a heavy load in Figure 6.20(c). PCV valve forced closed in the event of a backfire in Figure 6.20(d).

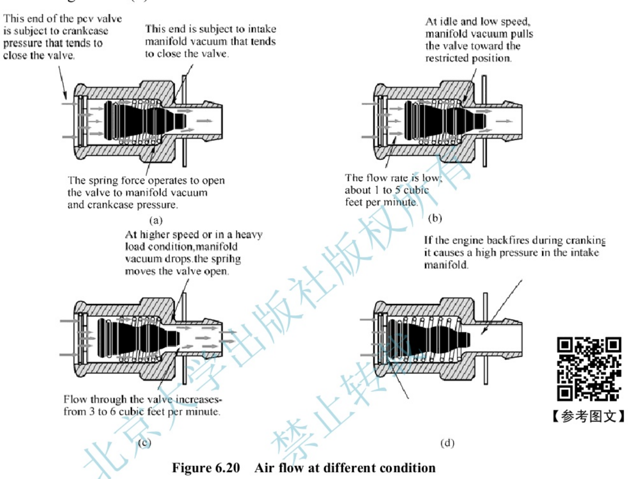



**Figure 6.20 Air flow at different condition**



## 6.5 On-board Refueling Vapor Recovery

### 6.5.1 General

On-board refueling vapor recovery (ORVR) is a vehicle emission control system that captures fuel vapors from the vehicle gas tank during refueling. The gas tank and fill pipe are designed so that when refueling the vehicle, fuel vapors in the gas tank travel to an activated carbon packed canister, which adsorbs the vapor. When the engine is in operation, it draws the gasoline vapors into the engine intake manifold to be used as fuel. In the United States, ORVR has been mandated on all passenger cars (phasing in over the 1998—2000 model years) and light trucks up to 10,000 lbs GVWR (phasing in over the 2001—2006 model years) by the United States Environmental Protection Agency. In EPA's recent Tier 3 automotive emission standard




rulemaking ORVR was extended to all complete gasoline-powered highway vehicles regardless of the GVWR. This takes effect in the 2018 model year. The use of ORVR is intended to make Stage II vapor recovery at gas stations obsolete. Many states in the US are now phasing out Stage II requirements because EPA has found that ORVR is in widespread use in the US (>75% of gasoline goes to ORVR-equipped vehicles) and the control by Stage II is largely redundant.

The on-board refueling vapor recovery system allows the fuel vapors in the fuel tank to be introduced directly into the canister through the vent valve when the fuel tank inside pressure increases as a result of refueling. The diagnosis of the system is performed by monitoring the fuel tank inside pressure data from the fuel tank pressure sensor while forcibly closing the drain valve.

### 6.5.2 Operation

#### 6.5.2.1 While driving

Since the back side of the diaphragm in the pressure control solenoid valve is open to the atmosphere, the diaphragm is held pressed by the atmospheric pressure in the position where only the external air is introduced into the canister. When the fuel vapor pressure acting on the other side of the diaphragm increases and overcomes the atmospheric pressure, it pushes the diaphragm and opens the port through which the fuel vapors make their way to the canister, as shown in Figure 6.21.



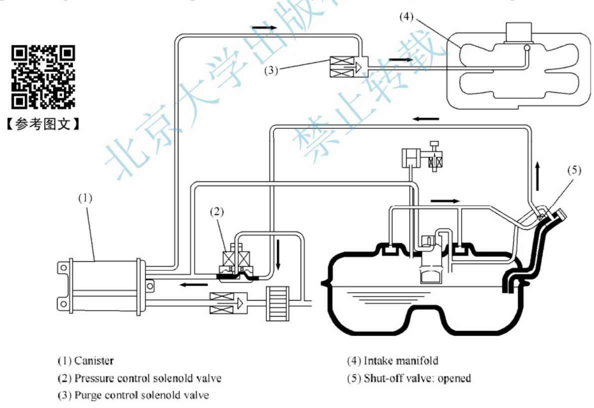



**Figure 6.21 Schematic diagram while driving**

#### 6.5.5.2 While refueling

As the fuel enters the fuel tank, the tank inside pressure increases. When the inside pressure

becomes higher than the atmospheric pressure, the port of the vent valve opens, allowing the fuel vapors to be introduced into the canister through the vent line. The fuel vapors are absorbed by charcoal in the canister, so the air discharged from the drain valve contains no fuel. When a filler gun is inserted, the shut-off valve closes the evaporation line, as shown in Figure 6.22.

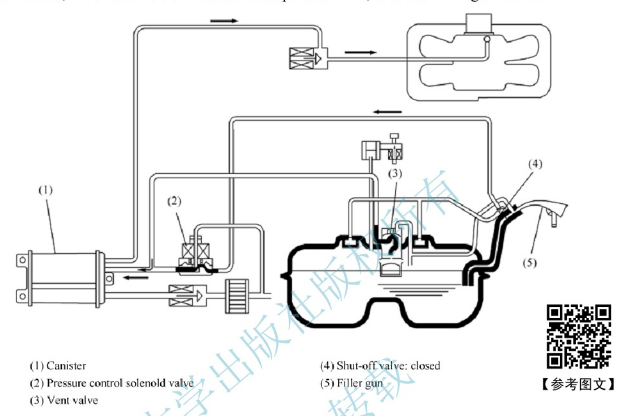



**Figure 6.22　Schematic diagram while refueling**





## Questions

1. What is A/F control?

2. Please summarize the principle of the electronic control system.

3. Where does the vapor of evaporative emissions come from?

4. What is on-board refueling vapor recovery?

5. How many simultaneous tasks does a two-way catalytic converter have? And please describe these tasks.

6. What is the advantage of a three-way catalytic converters?

7. How many simultaneous tasks does a three-way catalytic converter have? And please describe these tasks.

# Chapter 7

## RfcPcbsargml mdBgcqcj ClcglcqCk gqqgmlq




$NO_x$ emission limits are set for diesel engines depending on the engine maximum operating speed (n, rpm), as shown in Table 7.1 and presented graphically in Figure 7.1. Tier I and Tier II limits are global, while the Tier III standards apply only in $NO_x$ Emission Control Areas.

Table 7.1 MARPOL Annex VI $NO_x$ Emission Limits

| Tier | Date | $NO_x$ Limit, g/kWh | | |
|---|---|---|---|---|
| | | n<130 | 130≤n<2000 | n≥2000 |
| Tier I | 2000 | 17.0 | $45 \cdot n^{-0.2}$ | 9.8 |
| Tier II | 2011 | 14.4 | $44 \cdot n^{-0.23}$ | 7.7 |
| Tier III | 2016+ | 3.4 | $9 \cdot n^{-0.2}$ | 1.96 |

+ In $NO_x$ Emission Control Areas (Tier II standards apply outside ECAS).

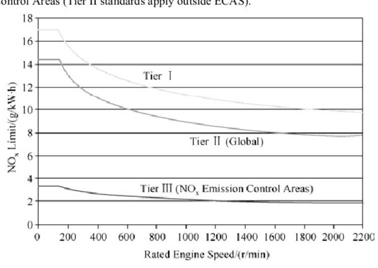



**Figure 7.1 $NO_x$ Emission Limits**

Question: How does a diesel engine reduce the $NO_x$ emission?

## 7.1 Diesel Engines

Diesel engines are important power systems for on-road and off-road vehicles. Most heavy-duty trucks and buses are powered by a diesel engine due to the long record of reliability, high fuel-efficiency, and high torque output. Diesel engines are easy to repair, inexpensive to operate, and extremely durable. It is not uncommon for a diesel engine to last 15–20 years and achieve a one million-mile life. From the standpoint of greenhouse gas emissions, diesel engines can compete with other advanced technologies, like hybrid electric vehicles, due to diesel's inherent fuel economy relative to conventional spark-ignited, gasoline engines. Diesel-powered vehicles have demonstrated a 30–40 percent fuel economy advantage over their gasoline counterparts. This translates to about a 20 percent reduction in $CO_2$ emissions.

While diesel engines have many advantages, they have the disadvantage of emitting significant amounts of particulate matter (PM) and oxides of nitrogen ($NO_x$) into the atmosphere. Diesel engines also emit toxic air pollutants. Health experts have concluded that pollutants emitted by diesel engines adversely affect human health and contribute to acid rain, ground-level ozone, and reduced visibility. Studies have shown that exposure to diesel exhaust causes lung damage and respiratory problems and there is increasing evidence that diesel emissions may cause cancer in humans.

Figure 7.2 shows the clear trend is toward reductions in PM and $NO_x$ usually in a two-stage approach. The first stage requires PM controls, such as diesel particulate filters. The second stage generally follows several years later with $NO_x$ controls. The trend is clearly toward technology-forcing regulations around the world requiring a systems approach that combines advanced combustion technology with additional exhaust controls for both PM and $NO_x$.



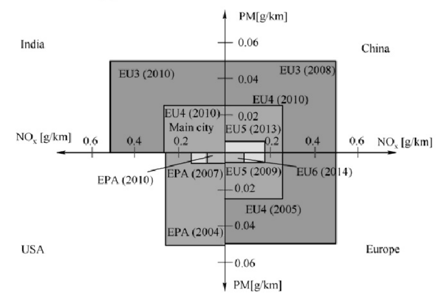



**Figure 7.2 The current and future emission regulations around the world for heavy-duty diesel engines**

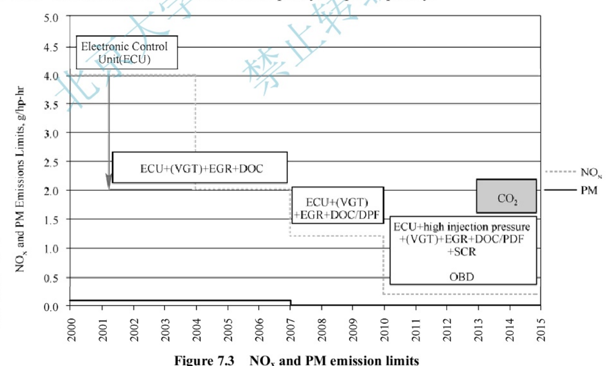
## 7.2　Available Control Technologies

Tailpipe emission concerns for diesel engines focus on gaseous emissions of HC and $NO_x$ (CO production is very small due to lean operation) and particulate matter (PM) emissions. PM consists primarily of soot on which other compounds are absorbed and results mostly from incomplete combustion.

Diesel engine calibration can be adjusted within the temperature-atmosphere combustion map into regions of higher PM or $NO_x$ emissions. A combustion environment that gives higher PM emissions will naturally result in lower $NO_x$ and vice-versa. Manufacturers can take advantage of this engine calibration control to specify a type of exhaust emission control that is best suited to meet regulations around the world. Therefore the technologies employed may vary depending on the demands of the emission standards in different countries.

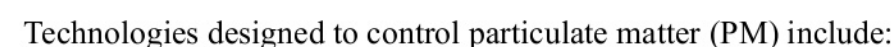
The $NO_x$ and PM emission limits, as shown in the Figure 7.3, would require a systems engineering approach with advanced engines and advanced exhaust emission control technologies. Low emissions demand that aftertreatment systems operate immediately after starting the engine. High activity catalyst formulations have low temperature light-off, and when combined with effective heat—and mass transfer and low heat capacity, respond quickly.






【参考图文】

**Figure 7.3　$NO_x$ and PM emission limits**



Technologies designed to control particulate matter (PM) include:

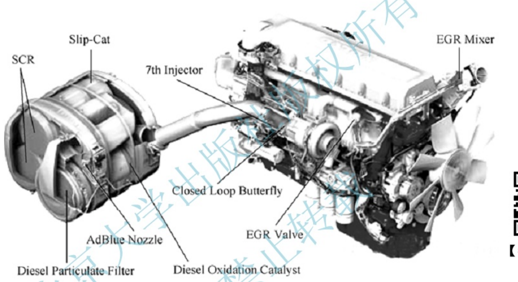
- Diesel oxidation catalysts (DOCs)

- Diesel particulate filters (DPFs)
- Closed crankcase ventilation (CCV)

Technologies designed to control oxides of nitrogen ($NO_x$) include:

- Exhaust gas recirculation (EGR)
- Selective catalytic reduction (SCR)
- Lean $NO_x$ catalysts (LNCs)
- Lean $NO_x$ traps (LNTs)

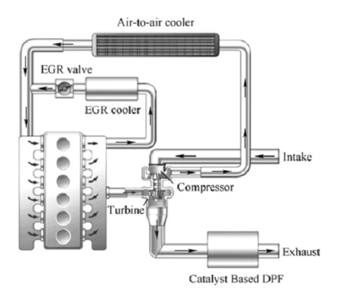
Today, viable emission control technologies exist to reduce diesel exhaust emissions from both new engines (Figure 7.4)and vehicles, as well as in-use engines through the use of retrofit kits. There is an example to meet the emission regulation in Figure 7.5. The major technologies are combined with DPF, DOC and EGR.






【参考图文】

**Figure 7.4　VOLVO D13K Euro 6 engine with EGR and after treatment muffler**






【参考图文】

**Figure 7.5　DPF+DOC+EGR**

# 7.3 Approaches for Reducing Diesel Emissions

## 7.3.1 Engine Controls

Engine manufacturers started as early as the late eighties to develop cleaner diesel engines by employing a number of strategies. These approaches include advanced common rail fuel injection, electronic engine controls, combustion chamber modifications, air boosting, improved air/fuel mixing, and reduced oil consumption. Achieving ultra-low exhaust emission targets requires a systems approach. Engine manufacturers are focusing on ways to control engine operation to reduce engine-out emissions as low as possible and reduce the burden on the exhaust emission control systems.

Approaches aimed at reducing cold-start emissions involve retarding the ignition timing to allow some hydrocarbons to pass through in the exhaust and light off the catalyst sooner. This approach can also be effective in generating sufficient exothermic heat over a catalyst to regenerate soot from a particulate filter as will be discussed in subsequent sections.

Variable valve timing (VVT) is being used to introduce some fraction of exhaust gas into the combustion process and reduce HC and $NO_x$ emissions. Exhaust gas recirculation (EGR) is used to dilute intake air with some fraction of exhaust gas to lower the combustion temperatures resulting in lower engine-out $NO_x$ emissions. This can come at the price of increasing particulate matter in the exhaust.

Direct injection of fuel into the cylinders rather than port injection has allowed for better control of the air fuel ratio during combustion and resulted in better fuel utilization. Improved turbulence and mixing in the intake port of some low emission engines have resulted in fuel savings. Advanced diesel engines have benefited significantly from common rail fuel injection which allows for electronically controlled injection at very high pressures. Through the use of pilot and retarded injection strategies or in combination with injection rate shaping, clean diesels have achieved significant reduction in $NO_x$ over conventional diesel injection such as pipe-line or unit injection. Common rail and electronic injection control is very effective in carefully controlling post injection of fuel, making it suitable for use with emission control devices such as particulate filters, $NO_x$ adsorbers and lean $NO_x$ catalysts requiring brief periods of fuel rich exhaust to facilitate regeneration of the catalyst or filter.

Understanding and controlling the combustion process is the first step in reducing engine-out emissions and minimizing the burden on the emission control systems. This allows catalyst developers to design smaller, less costly exhaust controls. Engine design is an important part of controlling and facilitating the combustion process.

In diesel engines, controlling combustion is the key approach to reducing engine-out

particulate emissions by optimizing the mixing between the fuel and air in the combustion chamber. Some common ways to increase mixing is through combustion chamber modifications to facilitate turbulent flow as well as fuel injector and injection port design to modify the spray pattern. Variable geometry turbocharging (VGT), which delivers variable quantities of pressurized air based on driving conditions, has been effective in reducing PM emissions by maintaining lean combustion in the engine. Reducing the compression ratios has been shown effective in lowering combustion temperatures and, in turn, $NO_x$ emissions.

Some engine manufacturers have been able to achieve improvements to combustion during cold-start by making modifications to the design of intake air control valves resulting in a 40–50 percent reduction in HC emissions.

State-of-the-art developments in combustion engineering has led to significant reductions in engine-out emissions on experimental engines. These processes are known by many names and acronyms but they all fall into the general classification of low temperature combustion or pre-mixed homogeneous combustion processes, such as homogeneous charge compression ignition (HCCI), among others.

The conventional wisdom in diesel combustion has been that any change in engine operating parameters to reduce $NO_x$ emissions results in an increase in particle emissions. In general, higher combustion temperatures promote complete oxidation of the fuel, thus less soot, but also cause more formation of $NO_x$. Unlike traditional spark-ignited (SI) or compression-ignited (CI) engines, which have specified ignition points, HCCI combustion takes place spontaneously and homogeneously with many nucleated ignition points and therefore without flame propagation. This eliminates heterogeneous air/fuel mixture regions which result in soot particles. Low temperature combustion can be facilitated by the use of ultrafine injector orifice diameters in conjunction with lower excess oxygen content in the fuel mixture to achieve a more homogeneous distribution of the charge, thus reducing both $NO_x$ and PM.

These combustion processes occur only within a limited range of the operating cycle, making control difficult under high speed/load and transient operation. For this reason, advanced multi-mode diesel engines combine HCCI operation at lower speeds to minimize PM and $NO_x$ while reverting to conventional stratified charge combustion at high speed/load operation to ensure stable operation.

### 7.3.2 Exhaust Controls

This section provides a brief description of the available diesel exhaust control technologies, including descriptions of their operating characteristics, control capabilities, and operating experience. More detail on each control technology is provided in subsequent sections.

The majority of hydrocarbon and carbon monoxide emissions from diesel engines that have exhaust catalysts occur during cold-start before the catalyst can achieve optimum operating temperatures. Engine and exhaust system manufacturers have been working together with catalyst

companies to develop ways to heat up the catalyst as quickly as possible. The greatest benefit came from the introduction of close-coupled catalysts (CCCs). This positioned the diesel oxidation catalyst (DOC) close to the exhaust manifold to allow rapid heating and therefore rapid oxidation of CO and hydrocarbons. The exothermic heat generated in the DOC by these oxidation reactions facilitates the rapid heat up of the downstream catalysts, such as diesel particulate filters, lean $NO_x$ catalysts, and SCR catalysts.

A supporting technology that links engine controls and exhaust controls and has been used effectively by both engine and exhaust technology developers is thermal management, as shown in Figure 7.6. The beneficial impact on reducing cold-start emissions via thermal management has resulted from numerous improvements to the exhaust system components upstream of the DOC in order to retain as much heat as possible in the exhaust gases. Manufacturers have developed ways to insulate the exhaust manifold and exhaust pipe. Attaching the DOC to a double-walled, stainless steel exhaust pipe containing an air gap within the tube walls is probably the most common thermal management strategy used today. This approach has been taken further by incorporating new inlet cone designs and modifications to the shape of the space in front of the close-coupled substrate. Thermal management between catalyst components in the diesel exhaust stream is also important to effectively regenerate the diesel particulate filter by retaining heat from the oxidation catalyst or auxiliary heat source when passive or active regeneration strategies are employed. Retaining enough heat downstream to regenerate a lean $NO_x$ trap also requires thermal management and carefully engineered exhaust components.



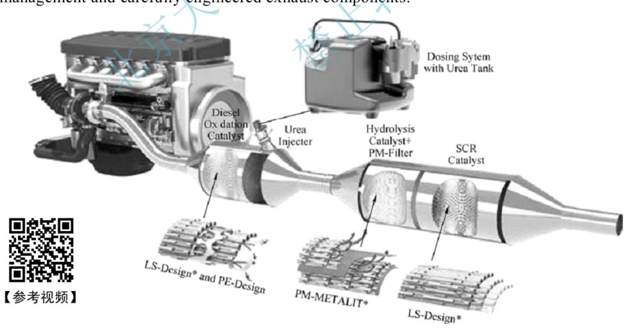



**Figure 7.6　An Exhaust Controls system**

Diesel oxidation catalysts (DOCs) installed on a vehicle's exhaust system can reduce total PM typically by as much as 25 to over 50 percent by mass, under some conditions depending on

the composition of the PM being emitted. Diesel oxidation catalysts can also reduce smoke emissions from older vehicles and virtually eliminate the obnoxious odors associated with diesel exhaust. Oxidation catalysts can reduce more than 90 percent of the CO and HC emissions and more than 70 percent of the toxic hydrocarbon emissions in diesel exhaust.

Diesel particulate filters (DPFs) are installed on all new diesel-powered vehicles to meet the U.S. Tier 2 light-duty and 2007 heavy-duty on highway emission limits for PM. DPFs can achieve up to, and in some cases, greater than a 90 percent reduction in PM. High efficiency filters are extremely effective in controlling the carbon fraction of the particulate, the portion of the particulate that some health experts believe may be the PM component of greatest concern. Particulate filters can be designed to also reduce toxic hydrocarbons emissions by over 90 percent. Catalytic exhaust control and particulate filter technologies have been shown to decrease the levels of polyaromatic hydrocarbons, nitro-polyaromatic hydrocarbons, and the mutagenic activity of diesel PM.

Exhaust gas recirculation (EGR) is being used on new light- and heavy-duty diesel vehicles as the primary method of reducing engine-out $NO_x$. EGR is capable of achieving a 50 percent reduction in $NO_x$. emissions or more; however, it can result in an increase in engine-out PM emissions.

$NO_x$ catalysts have demonstrated $NO_x$ reductions of 10 to 40 percent whereas $NO_x$ adsorbing catalysts (also known as $NO_x$ traps) are capable of 70 percent or more $NO_x$ reduction. These $NO_x$ catalysts also provide oxidation capabilities that result in significant reductions in exhaust hydrocarbons, CO and the soluble fraction of PM.

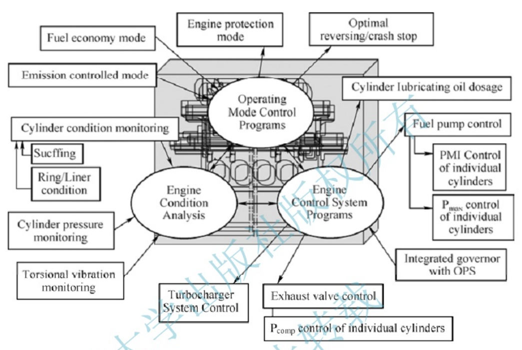
Selective catalytic reduction (SCR) using urea as a reducing agent has been shown to be the most effective control technology for reducing $NO_x$ emissions, exhibiting conversions of up to 90 percent while simultaneously reducing HC emissions by 50 to 90 percent and PM emissions by 30 to 50 percent.

Closed crankcase ventilation technology is being installed on all new heavy-duty trucks equipped with turbocharged diesel engines to eliminate crankcase emissions. Crankcase emissions vented to the engine compartment have been found to enter cabin air and can be a significant source of driver and passenger PM exposure. These systems capture particulate generated in the crankcase and return them to the lubricating system of the engine.

## 7.4 Intelligent Diesel Engine

The concept of the intelligent engine revolves around the idea that the engine is thinking for itself. The brain of the system is an electronic control system that analyzes the condition of the engine and the operation of the engine's system (The fuel injection, exhaust valve, cylinder lube oil and turbo charging system). Along with the control and timing needed to make the diesel run

smoothly, the intelligent diesel(See Figure 7.7) goes beyond that by monitoring and evaluating the condition of the engine, based on engine conditions the smart system can actively protect the engine from damage due to overload, lack of maintenance and maladjustment. The intelligent engines' finite control gives the bridge the ability to manually adjust more variables than the current camshaft system. Along with manual controls, operators can specifically design programs that optimize fuel economy, emission, turbo output, allowing for high performance under different loads.





【参考图文】

**Figure 7.7 Intelligent Diesel Engine**



A high pressure fuel injection system for an intelligent diesel engine (as shown in Figure 7.8) includes a fuel feed pump which pressurizes fuel to a given feed pressure during the engine being operated, while immediately stops pressurizing the fuel when the engine is stopped. The system further includes a high pressure supply pump connected in series to the fuel feed pump for further pressurizing the fuel supplied from the fuel feed pump to a higher pressure. The system further includes a high pressure fuel reservoir which receives the high pressure fuel from the high pressure supply pump and supplies it to fuel injection valves for injection therefrom. A pressure relief valve is connected to the high pressure fuel reservoir at its one side and to the fuel feed pump at its other side. The pressure relief valve is arranged to be held closed when the given feed pressure is applied thereto from the fuel feed pump, that is, when the engine is operated. On the other hand, the pressure relief valve is arranged to be immediately opened to release the pressure in the high pressure fuel reservoir in response to absence of the given feed pressure from the fuel feed pump, that is, when the engine is stopped. With this arrangement, leakage of the high pressure fuel via the fuel injection valves is effectively prevented.

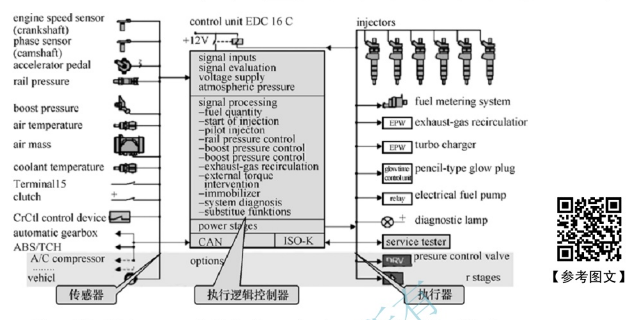



**Figure 7.8 High pressure fuel injection system for an intelligent Diesel Engine**

## 7.5 Flow-Through Diesel Oxidation Catalysts

The diesel oxidation catalyst (DOC) is one of the oldest forms of controlling exhaust pollutants such as CO, HC and PM. Originating from the early two-way automotive catalysts, DOCs are designed to oxidize unburned components of fuel in the exhaust to innocuous products like $CO_2$ and $H_2O$. The reactants may include exhaust hydrocarbons of all types, CO, or the soluble organic fraction (SOF) of the diesel particulate matter. The SOF consists of unburned hydrocarbons from fuel and lube oil that have condensed on the solid carbon particles.

DOCs are most often based on a flow-through honeycomb substrate (either metallic or ceramic), coated with an oxidizing catalyst such as platinum and/or palladium. Using oxidation catalysts on diesel-powered vehicles is not a new concept. Oxidation catalysts have been installed on over 250,000 off-road vehicles around the world for over 30 years. Tens of millions of oxidation catalysts have been installed on new diesel passenger cars in Europe and on new heavy-duty highway trucks in the U.S since the mid-1990s. These systems have operated trouble free for hundreds of thousands of miles. Oxidation catalysts can be used not only with conventional diesel fuel, but have also been shown effective with biodiesel and emulsified diesel fuels, ethanol/diesel blends and other alternative diesel fuels.

### 7.5.1 Diesel Oxidation Catalyst

In most applications, a diesel oxidation catalyst consists of a stainless steel canister that contains a honeycomb structure called a substrate or catalyst support. The substrate may be either made from a ceramic material or metal foil. There are no moving parts, just large amounts of interior surface area. The interior surfaces are coated with catalytic metals such as platinum and/or palladium.

This type of device is called an oxidation catalyst because it converts exhaust gas pollutants into harmless gases by means of chemical oxidation. In the case of diesel exhaust, the catalyst oxidizes CO, HCs, and the soluble organic fraction of particulate matter into carbon dioxide and water. DOCs also play an important role in continually removing soot from the DPF. This occurs by oxidizing some of the NO to $NO_2$ which serves to oxidize the soot or by generating heat through the oxidation of CO and HC to raise the DPF temperature above the soot oxidation temperature.

Figure 7.9 shows a representation of three channels of a straight through, flow path honeycomb. The engine-out exhaust gases enter the channels from the left and as they pass over the catalyst coating they are oxidized to the reaction products on the right. The particulate matter entering the DOC consists of elemental carbon (EC) and gaseous, semi-volatile SOF. Exiting the catalyst, most of the volatile SOF has been oxidized, as well as potentially some of the elemental carbon depending on the temperature. The level of total particulate reduction is influenced in part by the percentage of SOF in the particulate. Destruction of the SOF is important since this portion of the particulate emissions contains numerous chemical pollutants that are of particular concern to health experts.

【参考图文】

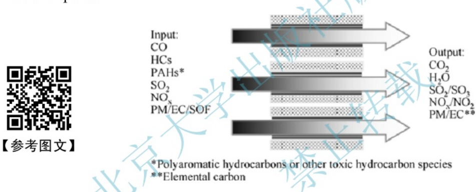



**Figure 7.9 Diagram of a Diesel Oxidation Catalyst.**



### 7.5.2 Filter Regeneration Catalysts

Now, all U.S. heavy- duty diesel vehicles must have a diesel particulate filter (DPF) in the exhaust system to reduce PM to below 0.01 g/bhp-hr. The DPF will be described in greater detail later in this report. An essential part of the proper functioning of any DPF system relies on a prescribed regeneration to occasionally burn soot collected in the filter and reduce the backpressure of the exhaust stream. Many exhaust control systems rely on a DOC or regeneration catalyst upstream of the DPF to assist with regeneration. This strategy can be applied to either coated or uncoated DPFs and essentially performs two functions. The first is to oxidize unburned HC and CO in the exhaust and utilize the exothermic heat of combustion to raise the temperature of the exhaust gas entering the DPF to temperatures sufficient to combust the captured carbonaceous soot. This can be done by enriching the fuel/air ratio going to the cylinders or injecting a small amount of fuel into the exhaust ahead of the DOC. A second DOC regeneration

function is to oxidize some of the $NO_x$ in the exhaust to nitrogen dioxide($NO_2$) which oxidizes carbon at a lower temperature than oxygen. The presence of higher concentrations of $NO_2$ thus facilitates filter regeneration at lower exhaust temperatures.

### 7.5.3 Impact of Sulfur on Oxidation Catalysts

The sulfur content of diesel fuel has a significant effect on the operation of catalyst technology. Catalysts used to oxidize the SOF of the particulate can also oxidize sulfur dioxide to form sulfate particulate (sulfates are a mixture of sulfuric acid and water), which adds to the mass of the particulate. This reaction is not only dependent on the level of sulfur in the fuel, but also the temperature of the exhaust gases. Diesel oxidation catalysts are the most sulfur resistant catalyst technologies being applied to diesel exhaust and were the only type of catalyst that could be used prior to the introduction of ULSD(ultra low sulful diesel). In most cases DOCs can operate effectively on fuel with up to 500 ppm/S, however the activity and function of the catalyst components can be impacted negatively, resulting in a reduction of catalyst efficiency.

Catalyst formulations have been developed which selectively oxidize the SOF while minimizing oxidation of the sulfur dioxide. However, the lower the sulfur content in the fuel, the greater the opportunity to maximize the effectiveness of oxidation catalyst technology for both better total control of PM and greater control of toxic HCs.



## 7.6 Particulate Filters

### 7.6.1 Operating Characteristics and Control Capabilities

As the name implies, diesel particulate filters remove particulate matter from diesel exhaust by filtering exhaust from the engine. They can be installed on vehicles or stationary diesel engines. Since a filter can fill up over time, engineers that design filter systems must provide a means of burning off or removing accumulated particulate matter. The only practical method of disposing of accumulated particulate matter is to burn or oxidize it within the filter when exhaust temperatures are adequate. By burning off trapped material, the filter is cleaned or “regenerated.” Filters that use available exhaust heat for regeneration are termed “passively regenerated” filters. Filters that regenerate in this fashion cannot be used in all situations. Filters that use some kind of energy input, like injection of diesel fuel into an upstream DOC, are termed “actively regenerated” filters. In general, new vehicle applications of DPFs employ a combination of passive and active regeneration strategies to ensure that filter regeneration occurs under all vehicle operating conditions. Active regeneration strategies employ various engine controls to achieve filter regeneration conditions on demand.

Diesel particulate filters can be combined with exhaust gas recirculation (EGR), $NO_x$

adsorber catalysts or selective catalytic reduction (SCR) to achieve significant $NO_x$ and PM reductions.

#### 7.6.1.1 Closed Crankcase Ventilation

In most turbocharged, after-cooled diesel engines, the crankcase is vented to the atmosphere often using a downward directed draft tube. While a rudimentary filter was often installed on the crankcase vent, substantial amount of particulate matter was released to the atmosphere. The particles are predominantly a liquid aerosol generated by the rapidly moving parts in the crankcase. When vented into the engine compartment, they are not only emitted, uncontrolled into the atmosphere, they can easily make their way into the passenger compartment of the vehicle. This PM goes undetected in any kind of engine-out PM measurement. Emissions through the crankcase vent may exceed 0.7 g/bhp-hr during idle conditions on recent model year engines.

Newer engines require the control of crankcase emissions and in many cases engine manufacturers are employing closed crankcase systems with filters as shown in Figure 7.10. This system consists of a multi-stage filter designed to collect, coalesce, and return the emitted lube oil to the engine’s sump. Filtered gases are returned to the intake system, balancing the differential pressures involved. Typical systems consist of a filter housing, a pressure regulator, a pressure relief valve and an oil check valve. These systems greatly reduce crankcase emissions. Closed crankcase filter systems can be combined with DOCs or DPFs to reduce PM emissions associated with both the ventilation of the crankcase and the tailpipe.




【参考图文】

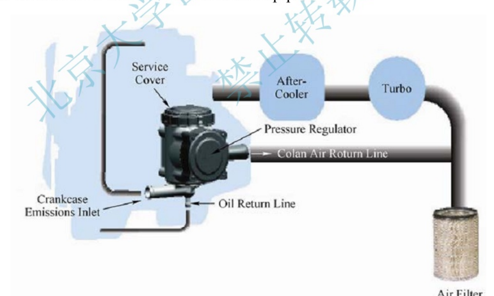
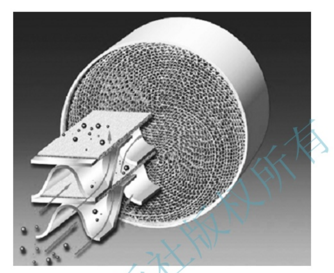



**Figure 7.10 Closed Crankcase Emission Control System**

#### 7.6.1.2 Flow-Through or Partial Diesel Particulate Filters

Flow-through filter technology is a relatively new method for reducing diesel PM emissions. Flow-through filters employ catalyzed metal wire mesh structures or tortuous flow, metal foil-based substrates with sintered metal sheets to reduce diesel PM (See Figure 7.11). Partial

Filters have been in production for more than 3 years with well over 200,000 pieces installed mostly in heavy-duty and light-duty vehicles in Europe. Because of their maintenance free operation, with no active regeneration or ash removal necessary, they are also verified as a level 2 (>50%–84%) PM reduction device under California's retrofit program. Flow-through filters are capable of achieving PM reduction of about 30 to 75 percent, depending on the engine operating characteristics.





【参考图文】

**Figure 7.11 Metallic flow-through filter made up of corrugated metal foil and layers of porous metal fleece**



Flow through filter technologies can be coated with catalyst materials to assist in oxidizing the soot or used in conjunction with an upstream diesel oxidation catalyst to oxidize diesel soot as the exhaust flows through these more turbulent flow devices. These metal devices may see advantages in applications requiring special shapes or having space limitations due to their relatively smaller package size. Flow-through filters generally do not accumulate inorganic ash constituents present in diesel exhaust. The ash passes through the device, reducing the need for filter cleaning in most applications.

### 7.6.2 High Efficiency Filters

In Europe, vehicles equipped with high efficiency diesel particulate filters are being offered commercially. Filters were introduced on new diesel passenger cars in Europe in mid-2000, with more than four million filter-equipped cars sold since that first introduction. Very few performance or maintenance issues have been reported in Europe with passenger car DPFs.

The most common high efficiency filter is based on a porous wall, square cell, honeycomb design where every alternate channel is plugged on each end. These wall-flow filters can be made from a variety of ceramic materials. High efficiency filters made of sintered metal fibers are also available. Wall-flow filters exhibit high strength and thermal durability.

Figure 7.12 simplifies the operation of a wall-flow DPF. Particulate-laden exhaust enters the filter from the left. To make the exhaust flow through the porous cell walls, channels are capped at

opposite ends in a checkerboard configuration. As the gas passes through the porous walls of the filter cells (thus the wall-flow filter designation) the particulate matter is deposited on the upstream side of the cell wall. Cleaned exhaust gas exits the filter to the right. Over time the soot deposited on the cell wall will result in a build-up of backpressure and will have to be cleaned by a process known as regeneration.

【参考图文】

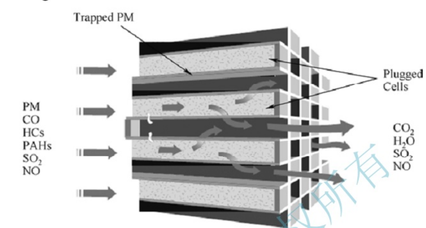



**Figure 7.12  Diagram of a Wall-Flow Diesel Particulate Filter**

Increasing interest has been raised regarding the health impacts of particulate size and number in addition to the total mass. At this time, research has not determined which physical characteristic or chemical component is the most significant. The European Union has actively pursued the measurement and characterization of ultrafine particles and particle number when promulgating new emission regulations. Future European light-duty emission standards will include emission limits for both PM mass and number. The future Euro VI heavy-duty standards being developed are also considering including requirements for both types of PM measurements.

The most commonly used ceramic materials for wall-flow DPFs are cordierite and silicon carbide. Cordierite has been used as a substrate material in exhaust catalysts for many years due to its strength, low thermal expansion coefficient (which makes it ideal in high thermal stress environments) and low cost. A high porosity version of cordierite was designed for wall-flow DPF applications. Most large heavy-duty diesel applications use cordierite filters. In contrast, most light-duty diesel passenger cars to date have been equipped with filters made from silicon carbide (SiC). SiC offers much higher temperature tolerance than cordierite for applications where exhaust or regeneration temperatures may require it. The high strength of SiC makes it suitable in high thermal stress exhaust environments. The combination of these properties allows for a higher soot loading limit as the higher thermal conductivity of SiC controls the peak temperature during regeneration. On the other hand, SiC has a higher thermal expansion coefficient than cordierite and requires a segmented architecture within the filter element. Other wall flow ceramic materials being offered commercially include aluminum titanate ($Al_2TiO_5$) and mullite ($Al_2SiO_5$) for their high temperature capability and thermal shock properties.

Filter efficiency has rarely been a problem with the filter materials listed above when applied

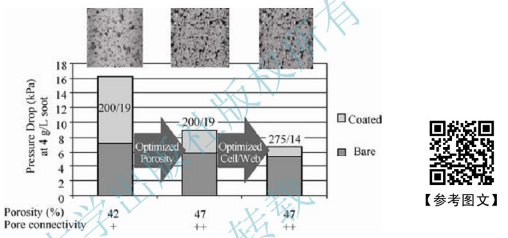
to wall-flow filter designs. Work has continued to:

a. optimize filter efficiency and minimize back pressure,

b. improve the radial flow of oxidation in thefilter during regeneration,

c. improve the mechanical strength of filter designs, and

d. increase the ash storage capacity of the filter. Technological developments in DPF design include advancements in cell shape and cell wall porosity optimization aimed at minimizing engine backpressure and extending the interval between filter service. Advances such as higher pore volume, increased pore connectivity along with thinner web designs facilitate catalyst coating while maintaining longer times between soot regeneration events. Figure 7.13 shows how these relative improvements in filter design benefit overall pressure drop. Shown are results for 200 cpsi/ 19 mil wall thickness and 275 cpsi/ 14 mil thin wall-flow ceramic filters.




【参考图文】

**Figure 7.13 Pressure drop across a wall-flow DPF loaded with 4 g/L of soot as a function of percent wall porosity and relative level of pore connectivity for catalyzed and uncatalyzed filters.**



## 7.7 Filter Regeneration

During normal operation of the diesel particulate filter, soot or particulate matter from the engine exhaust will be collected on the walls of the inlet channels. Since a filter will fill up over time, engineers that design filter systems must provide a means of burning off, or removing the accumulated particulate matter. A convenient means of removal of accumulated particulate matter is to burn or oxidize it on the filter when exhaust temperatures are adequate. By burning off trapped material, the filter is cleaned or “regenerated.” This is referred to as passive regeneration and will be covered in more detail below. Filters that regenerate in this fashion cannot be used in all situations, primarily due to insufficient exhaust gas temperatures associated with the operation of some types of diesel engines, the level of PM generated by a specific engine, and/or application operating experience. To ensure proper operation, filter systems are designed for the particular engine/vehicle application and account for exhaust temperatures and duty cycles of the specific

vehicle type. In low exhaust temperature operation an active regeneration strategy may need to be implemented to raise the exhaust temperature sufficient for oxidizing the soot.

Sulfur in diesel fuel significantly affects the reliability, durability, and emissions performance of catalyst-based DPFs. Sulfur affects filter performance by inhibiting the performance of catalytic materials upstream of or on the filter. Sulfur also competes with chemical reactions intended to reduce pollutant emissions and creates particulate matter through catalytic sulfate formation. Catalyst-based diesel particulate filter technology works best when the fuel sulfur level is less than 15 ppm. In general, the less sulfur in the fuel, the better the technology performs.

### 7.7.1 Passive Regeneration

The simplest type of filter is known as a passive design because it requires no driver or engine intervention to combust the soot on the filter. In this case the ceramic or metal filter substrate is coated with a high surface area oxide and precious or base metal catalyst. The catalyst acts to reduce the ignition temperature of the accumulated particulate matter by up to several hundred degrees centigrade. The reduction in ignition temperature allows the DPF to regenerate passively on some applications, but there will be others for which the exhaust temperature is too low to regenerate the filter. Because passive regeneration requires a minimum exhaust temperature, it is not applicable to all types of engines and vehicles.

The experience with catalyzed filters indicates that there is a virtually complete reduction in odor and in the soluble organic fraction of the particulate, but some catalysts may increase sulfate emissions. Companies utilizing these catalysts to provide regeneration for their filters have modified catalyst formulations to reduce sulfate emissions to acceptable levels. Ultra-low sulfur diesel fuel (15 ppm sulfur maximum) is now available in the U.S. and has greatly facilitated these efforts.

Catalyst-based passive regeneration also relies on an upstream oxidation catalyst to facilitate oxidation of nitric oxide (NO) to nitrogen dioxide ($NO_2$). Nitrogen dioxide is a much stronger oxidizer than oxygen, allowing filter regeneration at lower temperatures. The nitrogen dioxide oxidizes the collected particulate thus substantially reducing the temperature required to regenerate the filter.

### 7.7.2 Active Regeneration

Actively regenerated, high-efficiency filter systems can be applied to a much larger range of applications. Because of added complexity needed to expand the range, they are generally more expensive than passive filters. Some of the active technology options are burners (some operate while the engine is running, others operate while the engine is turned off), injection of diesel fuel into the exhaust stream for oxidation across a DOC upstream of the DPF, or electrical heaters.

The most commonly applied method of active regeneration is to introduce a temporary change in engine mode operation or an oxidation catalyst to facilitate an increase in exhaust temperature.

Engine mode strategies include:

a. Air-intake throttling. Throttling the air intake to one or more of the engine cylinders can increase the exhaust temperature and facilitate filter regeneration.

b. Post top-dead-center (TDC) fuel injection. Injecting small amounts of fuel in the cylinders of a diesel engine after pistons have reached TDC introduces a small amount of unburned fuel in the engine's exhaust gases. This unburned fuel can then be oxidized over an oxidation catalyst upstream of the filter or oxidized over a catalyzed particulate filter to combust accumulated particulate matter.

c. Post injection of diesel fuel in the exhaust upstream of an oxidation catalyst and/or catalyzed particulate filter. This regeneration method serves to generate heat used to combust accumulated particulates by oxidizing fuel across a catalyst present on the filter or on an oxidation catalyst upstream of the filter.

The above techniques can be used in combination with a catalyzed or uncatalyzed DPF.

In special applications where sufficient exhaust temperatures cannot be reached using the above techniques it may be necessary to use external means such as on-board fuel burners or electrical resistive heaters to heat the filter element and oxidize the soot. These can be used with catalyzed or uncatalyzed filter elements. In some cases regeneration can be accomplished while the vehicle is in operation, whereas in other cases the engine must be turned off for regeneration to proceed.

In some situations, installation of a filter system on a vehicle may cause a very slight fuel economy penalty. This fuel penalty is due to the backpressure of the filter system. As noted above, some filter regeneration methods involve the use of fuel burners and to the extent those methods are used, there will be an additional fuel economy penalty. Many filter systems, however, have been optimized to minimize, or nearly eliminate, any noticeable fuel economy penalty.

### 7.7.3 Fuel-Borne Catalysts



The widest experience with fuel-borne catalysts (FBC) has been demonstrated on European passenger vehicles where FBC in combination with high efficiency wall-flow filters have been used on new diesel cars since 2000. Fuel-borne catalysts are a colloidal dispersion of base metal oxides or organic compounds containing precious or base metal ions such as platinum, cerium or iron and are added to the diesel fuel prior to the combustion process. The catalyst is added in minute, parts per million level, quantities either directly to the fuel tank or mixed with the fuel on-board the vehicle prior to injecting the catalyst-fuel mixture into the cylinder. In the combustion process, the organic fraction of the additive is combusted leaving the inorganic metal or oxide catalyst finely distributed within the soot particles and other combustion products. The homogeneous distribution of the catalyst in the fuel prior to combustion results in a fine, intimate distribution of catalysts particles within the soot. The direct contact between catalyst particles and soot particles reduces the temperature required for ignition of trapped particulate matter that is collected together on the filter media. When used with high efficiency wall-flow filters, the catalyst remains in the filter media and adds to the inorganic ash that accumulates within the filter and must be periodically removed as part of a regularly scheduled filter maintenance program.

### 7.7.4 Filter Maintenance

In addition to collecting soot, filters also collect inorganic-based exhaust constituents that are derived from several sources, including the combustion of engine lubricants, products of normal engine wear and/or corrosion, and materials associated with fuel-borne catalysts in DPF applications that use these catalysts to assist in the filter regeneration process. These inorganic oxides do not combust during filter regeneration events. Over extended operation on the vehicle, these ash species slowly accumulate within the filter and gradually increase the pressure drop across the filter. Since excessively high backpressure on the engine will result in a degradation of engine performance, the accumulated ash material within the filter needs to be periodically removed. This ash removal or cleaning operation is a necessary filter maintenance operation. Engine oil consumption characteristics, the total ash content of engine lubricant formulations, vehicle duty cycles, filter designs, and fuel-borne catalyst dosing rates all impact ash accumulation profiles and required filter maintenance cleaning intervals. Because of the toxicity of the material in the DPF, filter cleaning must be done on special machines that will fully capture the material for safe disposal. Many diesel engine service facilities will have the machines.

Filter systems do not appear to cause any additional engine wear or affect vehicle maintenance. Concerning maintenance of the filter system itself, manufacturers are designing systems to minimize maintenance requirements during the useful life of the vehicle. Filter maintenance intervals are expected to exceed 300,000 miles of service. A new generation of low ash containing lubricants has been introduced for these heavy-duty engine applications to help maximize filter cleaning intervals.



## 7.8 $NO_x$ Reduction Technologies

The superior fuel economy of diesel engines over gasoline lies in their operation at high air to fuel ratios where there is excess oxygen. The oxygen-rich combustion environment in combination with high combustion temperatures results in the formation of nitrogen oxides ($NO_x$) in the combustion process. Gasoline engines also generate $NO_x$ by the same mechanisms; however, their typical stoichiometric air/fuel ratio in combination with three-way catalysts (TWCs) allows for very low tailpipe $NO_x$ levels. These approaches are generally not employed on diesel engines in order to maintain the significant fuel economy and low $CO_2$ benefits of these engines. Therefore, a new set of technologies have been developed by exhaust emission control manufacturers to significantly reduce $NO_x$ in oxygen-rich exhaust streams. Below is a brief overview of the types of technologies that are being developed and commercialized to reduce $NO_x$ from diesel engines and vehicles.

### 7.8.1 Exhaust Gas Recirculation (EGR)

As the name implies, EGR involves recirculating a portion of the engine's exhaust back to the charger inlet (or intake manifold in the case of naturally aspirated engines). In most systems, an intercooler lowers the temperature of the recirculated gases. The cooled recirculated gases, which have a higher heat capacity and lower oxygen content than air, lower the combustion temperature in the engine, thus inhibiting $NO_x$ formation. There are two types of EGR:

- *High pressure EGR* captures the exhaust gas prior to the turbocharger and redirects it back into the intake air.
- *Low pressure EGR* collects the clean exhaust after the turbocharger and after a diesel particulate filter and returns it to the intercooler. Diesel particulate filters are always used with a low-pressure EGR system to ensure that large amounts of particulate matter are not recirculated to the engine which would result in accelerated wear in the engine and turbocharger.

In some cases, engine manufacturers have also incorporated catalysts within high pressure EGR loops to reduce PM levels that are recirculated back through the combustion process. EGR systems typically recirculate about 25 to 40 percent of the combustion atmosphere to cool combustion temperatures and are capable of achieving $NO_x$ reductions of more than 40 percent. A schematic of a low-pressure EGR+DPF system is shown in Figure 7.14.



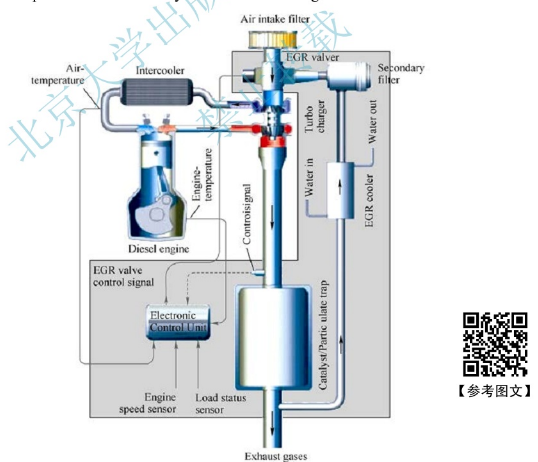



**Figure 7.14 Low Pressure Exhaust Gas Recirculation (EGR) + DPF**

【参考图文】

In order to optimize the engine-out $NO_x$ reduction over the largest portion of the engine map and improve the fuel economy at the same time, manufacturers have developed combined technology air breathing solutions. The benefits of variable turbine geometry (VTG) turbochargers and low pressure EGR have been combined to provide both efficiency and $NO_x$ reduction. At low engine speeds and loads, the low pressure EGR system maintains the energy flow to the turbine (and thus power and efficiency), while at higher speeds and high load portions of the engine map, the high pressure EGR system matches the flow requirements within the optimal turbine geometry to minimize losses. The blended EGR (high and low pressure) in combination with a VTG turbocharger can also match all operating conditions and provide better charge temperature control. The optimized combination of technologies is capable of achieving 30 percent $NO_x$ reduction while delivering a 3–4 percent reduction in brake specific fuel consumption (BSFC).

### 7.8.2 Lean $NO_x$ Catalysts

In the oxygen-rich environment of diesel exhaust, it is difficult to chemically reduce $NO_x$ to molecular nitrogen. Direct $NO_x$ decomposition is thermodynamically attractive, but the activation energy is very high for this method and no catalysts have been developed for wide-spread use.

Catalysts have been developed that use a reductant like HC, CO, or $H_2$ to assist in the conversion of $NO_x$ to molecular nitrogen in the diesel engine exhaust stream. They are generally called “lean $NO_x$ catalysts.” Because sufficient quantities of reductant are not present to facilitate $NO_x$ reduction in normal diesel exhaust, most lean $NO_x$ catalyst systems inject a small amount of diesel fuel, or other reductant, into the exhaust upstream of the catalyst. The added reductant allows for a significant conversion of $NO_x$ to $N_2$. This process is sometimes referred to as hydrocarbon selective catalytic reduction (HC-SCR). Currently, $NO_x$ conversion efficiencies using diesel fuel as the reductant are around 10 to 30 percent over transient test cycles. Other systems operate passively without any added reductant at reduced $NO_x$ conversion rates.

Lean $NO_x$ catalysts often include a porous material made of zeolite having a microporous, open framework structure providing trapping sites within the open cage network for hydrocarbon molecules along with either a precious metal or base metal catalyst. These microscopic sites facilitate reduction reactions between the trapped hydrocarbon molecules and $NO_x$.

### 7.8.3 Selective Catalytic Reduction (SCR)

SCR has been used to control $NO_x$ emissions from stationary sources such as power plants for over 20 years. More recently, it has been applied to select mobile sources including cars, trucks, marine vessels, and locomotives. Applying SCR to diesel-powered vehicles provides simultaneous reductions of $NO_x$, PM, and HC emissions. Many engine manufacturers

are now offering SCR systems on new highway heavy-duty engines sold in Europe to comply with the European Union's Euro IV or Euro V heavy-duty engine emission requirements. More than 100,000 new, SCR-equipped trucks are operating in Europe using a urea-based reductant.

SCR systems have also been installed on marine vessels, locomotives and other non-road diesel engines. Significant numbers of marine vessels have been equipped with SCR including auto ferries, transport ships, cruise ships, and military vessels. The marine engines range from approximately 1,250 hp to almost 10,000 hp and the installations have been in operation since the early to mid-1990s.

SCR offers a high level of $NO_x$ conversion with high durability. Open loop SCR systems can reduce $NO_x$ emissions from 75 to 90 percent. Closed loop systems on stationary engines have achieved $NO_x$ reductions of greater than 95 percent. Engine manufacturers here in North America are seriously considering combined DPF+SCR system designs for complying with EPA's 2010 heavy-duty highway emission standards. A number of combined DPF+SCR system demonstration projects have been completed or are still underway on highway trucks both here in the US and Europe. DOC+SCR systems are being used commercially in Japan for new diesel trucks by several engine manufacturers to comply with emission standards.

Modern SCR system designs combine highly controlled reductant injection hardware, flow mixing devices for effective distribution of the reductant across the available catalyst cross-section, durable SCR catalyst formulations, and ammonia slip clean-up catalysts that are capable of achieving and maintaining high $NO_x$ conversion efficiencies with extremely low levels of exhaust outlet ammonia concentrations over thousands of hours of operation.

In addition to $NO_x$, SCR systems reduce HC emissions up to 80 percent and PM emissions 20 to 30 percent. They also reduce the characteristic odor produced by a diesel engine and diesel smoke. Like all catalyst-based emission control technologies, SCR performance is enhanced by the use of low sulfur fuel. Combinations of DPFs and SCR generally require the use of ultra-low sulfur diesel to achieve the highest combined reductions of both PM and $NO_x$.

Significant advancements have been made not only to improve the catalyst performance and durability but also in the urea injection hardware to insure an accurate and well distributed supply of reductant. This insures that the entire catalyst volume is being utilized and the ammonia slip is minimized. Manufacturers are developing high precision injectors and mixer systems to disperse the reductant upstream of the catalyst. Urea injector suppliers are moving away from air driven injectors to airless designs to eliminate the need for air pumps specific to the urea supply.

A typical layout for an SCR system for heavy-duty highway vehicle is shown in Figure 7.15. In this system a DPF is followed by an SCR catalyst for combined reductions of both diesel PM and $NO_x$. A urea tank is positioned under the steps and is large enough to last over 10,000 miles of highway operation.


【参考图文】

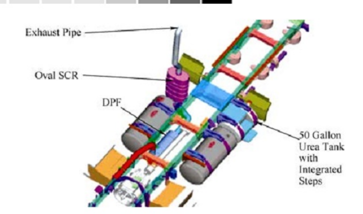



**Figure 7.15　An example of how a DPF/SCR catalyst system may be installed on an on-road Class 8 heavy duty truck chassis**

### 7.8.4　Combined LNT/SCR $NO_x$ Reduction Technologies

Engine and technology manufacturers are looking at novel approaches to address the need for alternative $NO_x$ control systems that do not require separate on-board reductant, like urea. These hybrid systems combine the catalyst functionality of lean $NO_x$ traps and ammonia SCR catalysts without the need for a second reductant on board the vehicle. These experimental systems typically incorporate a fuel reformer catalyst to generate a hydrogen rich reformate from the onboard fuel which is then used to regenerate the lean $NO_x$ trap. The regeneration of the LNT forms ammonia which is then stored within the SCR catalyst. The systems primarily rely on the LNT for the bulk of the $NO_x$ reduction during lean operation but the SCR uses the stored ammonia to further reduce $NO_x$, thereby extending the time between LNT regeneration and desulfations to reduce fuel penalties associated with these strategies.

An example of one of the designs being developed is illustrated in Figure 7.16. This design shows LNT and SCR catalysts in series and utilizes valves to bypass the LNT during regeneration. The reformate used to regenerate the LNT feeds ammonia rich gas to the SCR to achieve $NO_x$ reduction of the bypassed exhaust gas during this step.

Another example of an LNT plus SCR hybrid system is shown in Figure 7.17. This design shows the reformer, LNT and SCR catalyst all in series within the exhaust stream. In contrast to the system shown in Figure 7.16, this system does not require a bypass valve for LNT regeneration. The reformer processes the entire exhaust stream to generate the reductants used for LNT regeneration and ammonia formation.

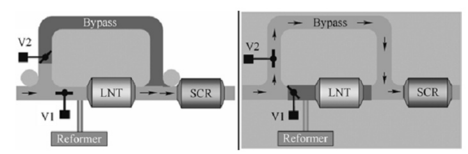



**Figure 7.16　LNT/SCR combined catalyst: parallel design**

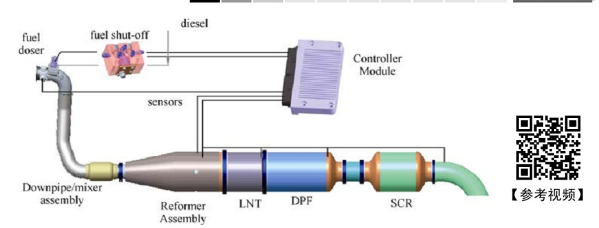



**Figure 7.17 LNT/SCR combined catalyst: series design**

The layered concept incorporates a first washcoat layer based on a $NO_x$ trap catalyst and an outer layer of an SCR catalyst composition. The ammonia that is released during regeneration of the trap is stored within the SCR layer and later utilized for selective catalytic reduction during lean operation.



## Questions

1. What are the main approaches to reduce diesel emissions?
2. What is intelligent diesel engine?
3. What is the impact of sulfur on oxidation catalysts?
4. Please summarize the principle of closed crankcase emission control system.
5. What is exhaust gas recirculation (EGR)?
6. What is selective catalytic reduction (SCR)?

# Chapter 8

## Ck gqqgml K _l_eck clr




A remote emission test equipment is seen on the road in Lanzhou, capital of northwest China's Gansu Province, Dec. 12, 2012, as shown in Figure 8.1. Two vehicles with the test system have been put into operation in Lanzhou recently. The system could collect and analyze emission data from a vehicle and record the vehicle number through a remote sensoring equipment without interrupting the traffic.





【参考视频】

**Figure 8.1 A remote emission test equipment**

Question: What are the advantages of remote emission test?

# 8.1 Emission Standards

Emission standards are legal requirements governing air pollutants released into the atmosphere. Emission standards set quantitative limits on the permissible amount of specific air pollutants that may be released from specific sources over specific time frames. They are generally designed to achieve air quality standards and to protect human health. Currently, emissions of nitrogen oxides ($NO_x$), total hydrocarbon (THC), non-methane hydrocarbons (NMHC), carbon monoxide (CO) and particulate matter (PM) are regulated for most vehicle types, including cars, lorries, trains, tractors and similar machinery, barges, but excluding seagoing ships and aeroplanes. For each vehicle type, different standards apply.

### 8.1.1 Regulated Sources

Many emissions standards focus on regulating pollutants released by automobiles (motor cars) and other powered vehicles. Others regulate emissions from industry, power plants, small equipment such as lawn mowers and diesel generators, and other sources of air pollution.

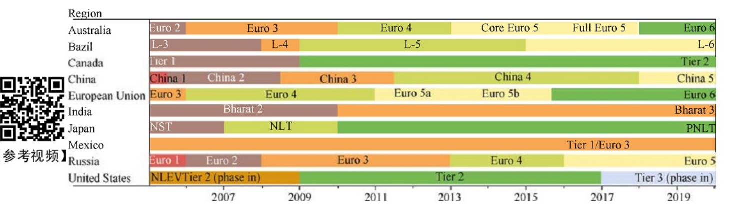


### 8.1.2 History and Current Status

The first legislated exhaust emission standards were promulgated by the State of California for 1966 model year for cars sold in that state, followed by the United States as a whole in model year 1968. The standards were progressively tightened year by year, as mandated by the EPA. By the 1974 model year, the emission standards had tightened such that the de-tuning techniques used to meet them were seriously reducing engine efficiency and thus increasing fuel usage. The new emission standards for 1975 model year, as well as the increase in fuel usage, forced the invention of the catalytic converter for after-treatment of the exhaust gas. This was not possible with existing leaded gasoline, because the lead residue contaminated the platinum catalyst. In 1972, General Motors proposed to the American Petroleum Institute the elimination of leaded fuels for 1975 and later model year cars. The production and distribution of unleaded fuel was a major challenge, but it was completed successfully in time for the 1975 model year cars. All modern cars are now equipped with catalytic converters and leaded fuel is nearly impossible to buy in most first world countries.

More and more countries are beginning to adhere to stricter emissions standards. Ten countries and regions have established or proposed their own motor emission standards in the Figure 8.2. These countries and regions cover most of the developed world and include the United States, European Union, Japan, Canada, and Australia. China and Russia have recently adopted new vehicle emission standards.




【参考视频】

**Figure 8.2 Worldwide emissions standards**

European emission standards define the acceptable limits for exhaust emissions of new vehicles sold in EU member states. The emission standards are defined in a series of European Union directives staging the progressive introduction of increasingly stringent standards. Emission standards for passenger cars and light commercial vehicles are summarized in the following tables. Since the Euro 2 stage, EU regulations introduce different emission limits for diesel and petrol vehicles. Diesels have more stringent CO standards but are allowed higher $NO_x$ emissions. Petrol-powered vehicles are exempted from particulate matter (PM) standards through to the Euro 4 stage, but vehicles with direct injection engines are subject to a limit of 0.005 g/km for Euro 5 and Euro 6. A particulate number standard (P) or (PN) has been introduced in 2011 with Euro 5b for diesel engines and in 2014 with Euro 6 for petrol engines, shown as in the Figure 8.3.

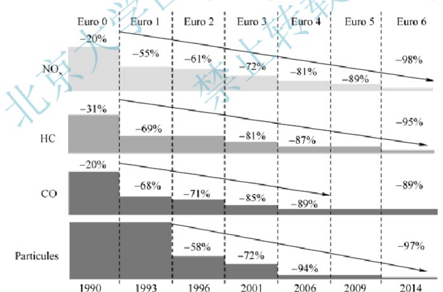



**Figure 8.3 European emission standards for passenger cars**

In China, the first emission regulations for motor vehicles became effective in the 1990s (Regulation GB 14761). Chinese standards, up to and including China 5, are based on European regulations, adopted with a certain time delay(See Figure 8.4). Table 8.1 is stage 5 emission limits in China.

In 2015, Beijing proposed standards for light-duty vehicles based on US Tier 3 limits. Once a

national standard has been issued, cities and regions in China may implement the standard in advance of the nationwide implementation dates, conditional on receiving approval from the State Council. In some cases, special approval can be granted to cities or regions to implement a stricter standard before the national standard has been released. Large metropolitan areas, including Beijing and Shanghai, Guangzhou, and some other cities have adopted more stringent regulations on an accelerated schedule, ahead of the rest of the country. Beijing implemented Euro 4 standards for light-duty vehicles in 2008 (the year of the Beijing Olympics) and Euro 5-based standards from 2013. Many cities in China use a system of colored labels attached to the vehicle to identify which vehicles meet the required emission standards.

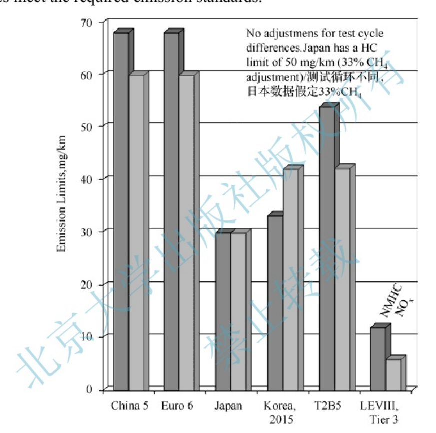




**Figure 8.4 $NO_x$ and NMHC Limits**

**Table 8.1 Stage 5 emission limits in China(g/km; PN: Particulate Number/km)**

| | CO | THC | NMHC | $NO_x$ | THC+$NO_x$ | PM | PN |
|---|---|---|---|---|---|---|---|
| China 5 | 1.00 | 0.100 | 0.068 | 0.060 | — | 0.0045 | $6\times10^{11}$ |
| China 4 | 1.00 | 0.100 | — | 0.080 | — | 0.0250 | — |
| China 3 | 2.30 | 0.200 | — | 0.150 | — | 0.0500 | — |

### 8.1.3 Vehicle Emission Performance Standard

An emission performance standard is a limit that sets thresholds above which a different type of emission control technology might be needed. While emission performance standards have been used to dictate limits for conventional pollutants such as oxides of nitrogen and oxides of

sulfur ($NO_x$ and $SO_x$), this regulatory technique may be used to regulate greenhouse gasses, particularly carbon dioxide ($CO_2$).

### 8.1.4 Obligatory Vehicle $CO_2$ Emission Limits

EU Regulation No 443/2009 sets an average $CO_2$ emissions target for new passenger cars of 130 grams per kilometre. The target is gradually being phased in between 2012 and 2015. A target of 95 grams per kilometre will apply from 2021.

For light commercial vehicle, an emissions target of 175 g/km applies from 2017, and 147 g/km from 2020.

## 8.2 On-board Diagnostics(OBD)

### 8.2.1 Basic Knowledge

#### 8.2.1.1 Definition

On-board diagnostics (OBD) is an automotive term referring to a vehicle's self-diagnostic and reporting capability, as shown in Figure 8.5. OBD systems give the vehicle owner or repair technician access to the status of the various vehicle subsystems. The amount of diagnostic information available via OBD has varied widely since its introduction in the early 1980s versions of on-board vehicle computers. Early versions of OBD would simply illuminate a malfunction indicator light or "idiot light" if a problem was detected but would not provide any information as to the nature of the problem. Modern OBD implementations use a standardized digital communications port to provide real-time data in addition to a standardized series of diagnostic trouble codes, (or DTCs), which allow one to rapidly identify and remedy malfunctions within the vehicle.




【参考视频】




**Figure 8.5 OBD connector on a vehicle**

### 8.2.1.2 OBD-I

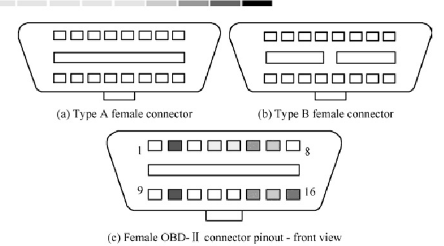
The regulatory intent of OBD-I was to encourage auto manufacturers to design reliable emission control systems that remain effective for the vehicle's "useful life". The Diagnostic Trouble Codes (DTCs) of OBD-I vehicles can usually be found without an expensive "scan tool". Each manufacturer used its own diagnostic link connector (DLC), DLC location, DTC definitions, and procedure to read the DTCs from the vehicle. DTCs from OBD-I cars are often read through the blinking patterns of the "Check Engine Light" (CEL) or "Service Engine Soon" (SES) light. By connecting certain pins of the diagnostic connector, the "Check Engine" light will blink out a two-digit number that corresponds to a specific error condition. The DTCs of some OBD-I cars are interpreted in different ways, however. Cadillac (gasoline) fuel-injected vehicles are equipped with actual on-board diagnostics, providing trouble codes, actuator tests and sensor data through the new digital electronic climate control display. Holding down "Off" and "Warmer" for several seconds activates the diagnostic mode without the need for an external scan tool.

### 8.2.1.3 OBD-II

OBD-II is an improvement over OBD-I in both capability and standardization. The OBD-II standard specifies the type of diagnostic connector and its pinout, the electrical signalling protocols available, and the messaging format. It also provides a candidate list of vehicle parameters to monitor along with how to encode the data for each. There is a pin in the connector that provides power for the scan tool from the vehicle battery, which eliminates the need to connect a scan tool to a power source separately. However, some technicians might still connect the scan tool to an auxiliary power source to protect data in the unusual event that a vehicle experiences a loss of electrical power due to a malfunction. Finally, the OBD-II standard provides an extensible list of DTCs. As a result of this standardization, a single device can query the on-board computer(s) in any vehicle. This OBD-II came in two models OBD-IIA and OBD-IIB. OBD-II standardization was prompted by emissions requirements, and though only emission-related codes and data are required to be transmitted through it, most manufacturers have made the OBD-II Data Link Connector the only one in the vehicle through which all systems are diagnosed and programmed. OBD-II Diagnostic Trouble Codes are 4-digit, preceded by a letter: P for engine and transmission (powertrain), B for body, C for chassis, and U for network.

### 8.2.1.4 OBD-II diagnostic connector

The SAE J1962 specification provides for two standardized hardware interfaces, called type A and type B,as shown in Figure 8.6. Both are female, 16-pin (2×8), D-shaped connectors, and both have a groove between the two rows of pins. But type B has the groove interrupted in the middle, so you can't plug a type A male connector into a type B socket. You can, however, mate a type B male plug in a type A female socket.



(a) Type A female connector (b) Type B female connector

(c) Female OBD-Ⅱ connector pinout - front view

【参考视频】

**Figure 8.6  Two standardized hardware interfaces**

The type A connector is used for vehicles that use 12V supply voltage, whereas type B is used for 24V vehicles and it is required to mark the front of the D-shaped area in blue color.

Unlike the OBD-I connector, which was sometimes found under the hood of the vehicle, the OBD-II connector (as shown in Figure 8.7) is required to be within 2 feet (0.61 m) of the steering wheel (unless an exemption is applied for by the manufacturer, in which case it is still somewhere within reach of the driver).





**Figure 8.7  Female OBD-II connector on a car**

### 8.2.1.5 OBD-II diagnostic data available

OBD-II provides access to data from the engine control unit (ECU) and offers a valuable source of information when trouble-shooting problems arise inside a vehicle. The SAE J1979 standard defines a method for requesting various diagnostic data and a list of standard parameters that might be available from the ECU. The various parameters that are available are addressed by "parameter identification numbers" or PIDs which are defined in J1979. For a list of basic PIDs, their definitions, and the formula to convert raw OBD-II output to meaningful diagnostic units, see OBD-II PIDs. Manufacturers are not required to implement all PIDs listed in J1979 and they

are allowed to include proprietary PIDs that are not listed. The PID request and data retrieval system gives access to real time performance data as well as flagged DTCs. For a list of generic OBD-II DTCs suggested by the SAE, see Table of OBD-II Codes. Individual manufacturers often enhance the OBD-II code set with additional proprietary DTCs.

### 8.2.2 OBD Applications

Various tools are available that plug into the OBD connector to access OBD functions. These range from simple generic consumer level tools to highly sophisticated OEM dealership tools to vehicle telematic devices.

#### 8.2.2.1 Hand-held scan tools

Multi-brand vehicle diagnostics system handheld Autoboss V-30 with adapters for connectors of several vehicle manufacturers, as shown in Figure 8.8. A range of rugged hand-held scan tools is available.

- Simple fault code readers/reset tools are mostly aimed at the consumer level.
- Professional hand-held scan tools may possess more advanced functions.
  - Access more advanced diagnostics.
  - Set manufacturer- or vehicle-specific ECU parameters.
  - Access and control other control units, such as air bag or ABS.
  - Real-time monitoring or graphing of engine parameters to facilitate diagnosis or tuning.








【参考视频】

**Figure 8.8 Multi-brand vehicle diagnostics system handheld Autoboss V-30 with adapters for connectors of several vehicle manufacturers**

#### 8.2.2.2 Mobile device-based tools and analysis

Mobile device applications allow mobile devices such as cell phones and tablets to display and manipulate the OBD-II data accessed via USB adaptor cables, bluetooth or WiFi adapters plugged into the car's OBD II connector. Figure 8.9 is a simple, rugged muti-brand haudheld scanner.




【参考视频】

Figure 8.9 Simple, rugged multi-brand handheld scanner

### 8.2.2.3 PC-based scan tools and analysis platforms

Typical simple USB KKL Diagnostic Interface without protocol logic for signal level adjustment is shown in Figure 8.10. A PC-based OBD analysis tool that converts the OBD-II signals to serial data (USB or serial port) standard to PCs or Macs. The software then decodes the received data to a visual display. Many popular interfaces are based on the ELM or STN1110 OBD Interpreter ICs, both of which read all five generic OBD-II protocols. Some adapters now use the J2534 API allowing them to access OBD-II Protocols for both cars and trucks.





【参考图文】

Figure 8.10 Typical simple USB KKL Diagnostic Interface without protocol logic for signal level adjustment

In addition to the functions of a hand-held scan tool, the PC-based tools generally offer:

- ✧ Large storage capacity for data logging and other functions
- ✧ Higher resolution screen than handheld tools
- ✧ The ability to use multiple software programs adding flexibility to the extent that a PC tool may access manufacturer or vehicle-specific ECU diagnostics varies between software products as it does between hand-held scanners.

#### 8.2.2.4 Data loggers

TEXA OBD log, small data logger with the possibility to read out the data later on PC via USB is shown in Figure 8.11. Data loggers are designed to capture vehicle data while the vehicle is in normal operation, for later analysis.

Data logging uses include:

- ✧ Engine and vehicle monitoring under normal operation, for the purpose of diagnosis or tuning.
- ✧ Some auto insurance companies offer reduced premiums if OBD-II vehicle data loggersor cameras are installed—and if the driver's behaviour meets requirements. This is a form of auto insurance risk selection.
- ✧ Monitoring of driver behaviour by fleet vehicle operators.





【参考视频】

**Figure 8.11 TEXA OBD log. Small data logger with the possibility to read out the data later**



Analysis of vehicle black box data may be performed on a periodic basis, automatically transmitted wirelessly to a third party or retrieved for forensic analysis after an event such as an accident, traffic infringement or mechanical fault.

#### 8.2.2.5 Emission testing

In the United States, many states now use OBD-II testing instead of tailpipe testing in OBD-II compliant vehicles (1996 and newer). Since OBD-II stores trouble codes for emissions equipment, the testing computer can query the vehicle's on-board computer and verify there are no emission related trouble codes and that the vehicle is in compliance with emission standards for the model year it was manufactured. In the Netherlands, 2006 and later vehicles get a yearly EOBD emission check. The principle on OBD for vehicle Emission control system is shown as the Figure 8.12.

#### 8.2.2.6 Vehicle telematics

OBD II is no longer only used by professionals and hobbyists to repair vehicles. OBD II information is commonly used by vehicle telematics devices that perform fleet tracking, monitor

fuel efficiency, prevent unsafe driving, as well as for remote diagnostics and by pay-as-you-drive insurance, as shown in Figure 8.12. Although originally not intended for the above purposes, commonly supported OBD II data such as vehicle speed, RPM, and fuel level allow GPS-based fleet tracking devices to monitor vehicle idling times, speeding, and over-revving. By monitoring OBD II DTCs a company can know immediately if one of its vehicles has an engine problem and by interpreting the code the nature of the problem. OBD II is also monitored to block mobile phones when driving and to record trip data for insurance purposes.

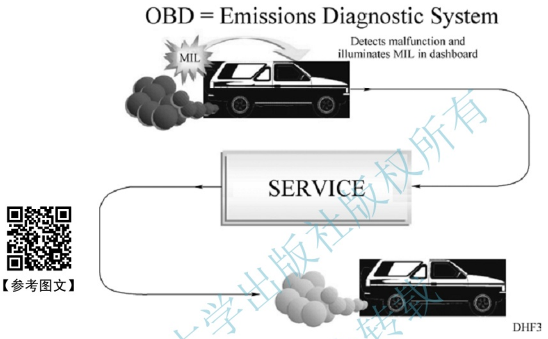



**Figure 8.12　OBD for vehicle Emission control system**



## 8.3　Portable Emissions Measurement System

### 8.3.1　Definition

A portable emissions measurement system (PEMS) is essentially a lightweight “laboratory” that is used to test and/or assess mobile source emissions (i.e. cars, trucks, buses, construction equipment, generators, trains, cranes, etc.) for the purposes of compliance, regulation, or decision-making, as shown in Figure 8.13. Early examples of portable vehicle emissions equipment were developed and marketed by Warren Spring Laboratory UK during the early 1990’s. This equipment was used to measure on-road emissions as part of the UK Environment Research Programme. The concept of “in-use” emissions and fuel economy testing was introduced by Leo Breton, an EPA engineer working in the emissions compliance area. Governmental entities like United States Environmental Protection Agency (USEPA), European Union, as well as various states and private sector entities have begun to utilize PEMS in order to reduce both the

costs and time involved in making mobile emissions decisions. Various state, federal, and international agencies began referring to this shorthand term in early 2000, and the nickname became part of industry parlance.

### 8.3.2 On-road Emissions Patterns Identified by PEMS





【参考视频】

**Figure 8.13 A standalone PEMS solution**

Nearly all modern engines, when tested new and according to the accepted testing protocols in a laboratory, produce relatively low emissions well within the set standards. As all individual engines of the same series are supposed to be identical, only one or several engines of each series get tested. The tests have shown that:

- ✧ The bulk of the total emissions can come from relatively short high-emissions episodes;
- ✧ Emissions characteristics can be different even among otherwise identical engines;
- ✧ Emissions outside of the bounds of the laboratory test procedures are often higher than under the operating and ambient conditions comparable to those during laboratory testing;
- ✧ Emissions deteriorate significantly over the useful life of the vehicles;
- ✧ There are large variances among the deterioration rates, with the high emissions rates often attributable to various mechanical malfunctions.



These findings are consistent with published literature, and with the data from a myriad of subsequent studies. They are more applicable to spark-ignition engines and considerably less to diesels, but with the regulation-driven advances in diesel engine technology (comparable to the advances in spark-ignition engines since the 1970s) it can be expected that these findings are likely to be applicable to the new generation diesel engines. Since 2000, multiple entities have utilized PEMS data to measured in-use, on-road emissions on hundreds of diesel engines installed in school buses, transit buses, delivery trucks, plow trucks, over-the-road trucks, pickups, vans, forklifts, excavators, generators, loaders, compressors, locomotives, passenger ferries, and other on-road, off-road and non-road applications. All the previously listed findings were demonstrated; in addition, it was noticed that extended idling of engines can have a significant impact on the emissions during subsequent operation.

Also, PEMS testing identified several engine “anomalies” where fuel-specific $NO_x$ emissions were two to three times higher than expected during some modes of operation, suggesting deliberate alterations of the engine control unit (ECU) settings. Such data set can be readily used for developing emissions inventories, as well as to evaluate various improvements in engines, fuels, exhaust after-treatment and other areas. (Data collected on “conventional” fleets then serves as “baseline” data to which various improvements are compared.) This data set can also be

examined for compliance with not-to-exceed (NTE) and in-use emissions standards, which are "US-based" emission standards that require on-road testing.

### 8.3.3 Advantages of PEMS

On-road vehicle emissions testing is very different from the laboratory testing, bringing both considerable benefits and challenges. As the testing can take place during the regular operation of the tested vehicles, a large number of vehicles can be tested within a relatively short period of time and at relatively low cost. Engines that cannot be easily tested otherwise (i.e., ferry boat propulsion engines) can be tested. True real-world emissions data can be obtained. The instruments have to be small, lightweight, withstand difficult environment, and must not pose a safety hazard. Emissions data is subject to considerable variances, as real-world conditions are often neither well defined nor repeatable, and significant variances in emissions can exist even among otherwise identical engines. On-road emissions testing therefore requires a different mindset than the traditional approach of testing in the laboratory and using models to predict real-world performance. In the absence of established methods, use of PEMS requires careful, thoughtful, broad approach. This should be considered when designing, evaluating and selecting PEMS for the desired application.

## 8.4 Emission Trading



### 8.4.1 Definition

Emissions trading or cap-and-trade is a government-mandated, market-based approach to controlling pollution by providing economic incentives for achieving reductions in the emissions of pollutants. Various countries, states and groups of companies have adopted such trading systems, notably for mitigating climate change.

A central authority (usually a governmental body) allocates or sells a limited number of permits to discharge specific quantities of a specific pollutant per time period. Polluters are required to hold permits in amount equal to their emissions. Polluters that want to increase their emissions must buy permits from others willing to sell them. Financial derivatives of permits can also be traded on secondary markets.

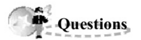
In theory, polluters who can reduce emissions most cheaply will do so, achieving the emission reduction at the lowest cost to society. Cap and trade is meant to provide the private sector with the flexibility required to reduce emissions while stimulating technological innovation and economic growth.

### 8.4.2 Pollution Tax

Emissions fees or environmental tax is a surcharge on the pollution created while producing goods and services. For example, a carbon tax is a tax on the carbon content of fossil fuels that

aims to discourage their use and thereby reduce carbon dioxide emissions. The two approaches are overlapping sets of policy designs. Both can have a range of scopes, points of regulation, and price schedules. They can be fair or unfair, depending on how the revenue is used. Both have the effect of increasing the price of goods (such as fossil fuels) to consumers. A comprehensive, upstream, auctioned cap-and-trade system is very similar to a comprehensive, upstream carbon tax. Yet, many commentators sharply contrast the two approaches.

The main difference is what is defined and what derived. A tax is a price control, while cap-and-trade method acts is a quantity control instrument. That is, a tax is a unit price for pollution that is set by authorities, and the market determines the quantity emitted; incap-and-trade, authorities determine the amount of pollution, and the market determines the price. This difference affects a number of criteria.



**Questions**

1. What is on-board diagnostics(OBD)?
2. What are the advantages of PEMS?
3. What are the applications of OBD?